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THE CONCEPT OF THE GRADED RIVER

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ABSTRACT

The concept of the river at grade assumes the attainment of a balance between power and load. A critical review of the original sources responsible for this notion of balance in stream work, particularly A. Surell and G. K. Gilbert, reveals that this equilibrium is only a postulate which remains unsupported by observations and that the attributes commonly associated with a graded river, like absence of downward corrasion and efficiency in lateral erosion, are incompatible with the postulate of balance between power and load. Consideration of the common variations in volume of flow and of the importance of turbulence in transportation of debris suggests impossibility of maintenance and even of acquisition of a full load. The customary notion of a graded river as a stream in which equilibrium between power and load is maintained must be discarded, and the term restricted to mean a river without waterfalls and rapids. Discard of this idea of balance in stream work should lead to a better understanding of the role of corrasion, alluviation, and weathering of slopes in valley sculpture.

INTRODUCTION

A stock concept of geomorphology, especially in this country, is the postulate of the graded river, or river at grade. In such a river the amount of energy not spent in the movement of the water is held to balance exactly the energy required for the transportation of the total load of the river. A river which has attained this condition of balance or equilibrium thereby becomes incapable of any erosive action but remains competent for the continued transportation of its load. A graded river thus neither degrades nor aggrades its bed.

This condition of grade has been assumed to be characteristic of mature rivers or mature sectors of rivers and has been postulated as continuing into the old age of streams. In meandering rivers, held

to be mature, increase of load through the obvious erosive action on bends is assumed to be balanced by an equal amount of deposition on the convex bank. In the continued flattening of the longitudinal profile of a river between maturity and old age the rate of lowering of the gradient is claimed to be too small materially to affect the postulated balance between power and load. Continuance of the graded condition from maturity into old age is thus assured.

The improbability of the continued maintenance of balance between energy and load in all parts of a river and the difficulty of associating erosion in meander bends, or between maturity and old age, with the postulate of graded conditions prompt a critical review of this concept.

HISTORICAL REVIEW

The concept of the graded river was introduced into and firmly established in American physiographic literature through the teaching and extensive writing of William Morris Davis. The assumption of balanced conditions in stream work, however, is not original with Davis, who gives credit for this idea to Gilbert and M. Dausse, a French engineer. Albert Heim developed similar views in studying river work in the Swiss Alps during the 1870's, while Italian hydrologic engineers had been familiar with such concepts for more than a century prior to that date.

Italian and French engineers and geomorphologists drew the logical conclusions from the postulate of balance, assumed to exist either between power and load or between energy of the water and resistance of the bed, and saw in its attainment the end of all erosion. Davis, however, saw grade established relatively early in the history of rivers, at the beginning of maturity. He, therefore, refuted the conclusion that establishment of grade indicates the end of erosion by a river and postulated that the balance between ability and work, while remaining a balance, undergoes slight modifications permitting erosion.

Davis himself introduced his concept of the graded river, together with his geographical cycle, into European geomorphology. At first very enthusiastically received by a group of younger German geographers, both the cycle and the graded river have since been discarded by most geomorphologists in Germany. Graded conditions

are regarded either as characteristic of but limited sections of rivers or as attainable by the whole river only at the end of the erosive process. It is especially A. Phillippson who has defended the latter position ever since 1886, basing his conclusions on the same sources which led Davis to his concept of grade in streams, that is, the writings of Gilbert and of French hydrologic engineers.

In France the geographical cycle was accepted and retained by most morphologists; Davis' concept of the graded river, by only a few. Most French morphologists regard graded conditions of a river as an indication of the end of all erosion. Italian morphologists seem to think likewise. In England and its dominions Davis' concept of grade in rivers has been accepted to a considerable degree, although some skepticism is occasionally expressed.

In the United States most authors adhere to the teaching of Davis. A few textbooks omit the topic of grade in rivers, but no dissenting voice seems to the writer to have made itself heard.

EVIDENCE OF GRADED CONDITIONS IN A RIVER

Although the geographical cycle, of which the graded river forms an integral part, was presented by its author in a deductive form, demanding no proof, care nevertheless was taken to show its validity by introducing numerous examples from land forms of today which verified the deductions. One looks in vain among these different examples for the river showing typical graded conditions. Only two references to grade in actual rivers have come to my attention in the writings of Davis. In his lectures delivered at the University of Berlin he introduced the Colorado River in the Grand Canyon as an essentially graded river, reasoning as follows: "As far as we can see, the stream flows along the floor without waterfalls or rapids, i.e., appears essentially to have reached grade."[1]

The graded condition which was defined as a balance between power and load is here shown to exist by the lack of waterfalls and rapids, that is, features of youth. Instead of being demonstrated, the postulated balance is only implied from the assumed stage of maturity in valley development.

[1] Davis-Rühl, *Die erklärende Beschreibung der Landformen* (Berlin and Leipzig: B. G. Teubner, 1912), p. 90.

The other example of a graded river, given by Davis, reads as follows: "The Elbe above Dresden offers illustration of a later stage . . . . it has the beginnings of a flood plain, now on one side, now on the other side of the river; from which it is inferred that the deepening of the valley has practically ceased, that the river is graded."[2]

The criterion of grade—balance between power and load—is again not demonstrated, and the balanced condition is only inferred from attained maturity.

H. Baulig, the major advocate in France of Davis' physiography, also attempted to establish criteria for graded conditions in rivers. Assuming that a graded river should flow upon a bed of continuous alluvium which it neither degrades nor aggrades markedly, he concluded that such a river should not show signs of recent degradation, such as river terraces, or of aggradation, such as natural levees, irregular meanders of reduced size, or deferred junction of tributaries.[3]

The assumption that a graded river should flow on a bed of alluvial material can rightfully be criticized, as a continuous layer of alluvium would indicate persistent aggradation instead of ability of the stream to transport all its load. The criteria appear even to imply the occurrence of a flood plain—a definite feature of repeated and extensive alluviation which is a process incompatible with the condition of grade in rivers. The proposed criteria would be rational only if, following many authorities, flood plains are interpreted as erosional features. The postulated balance between power and load would still remain undemonstrated, however, as it would only be implied from the assumed absence of net erosion or net deposition.

As it seems so difficult to recognize a graded river and apparently impossible to establish criteria which would allow the direct detection of graded conditions in a river itself or in its bed, is it not understandable that one may doubt this postulated perfect balance between power and load?

[2] "Physical Geography as a University Study," *Geographical Essays* (Boston: Ginn & Co., 1909), p. 185. Originally published in *Jour. Geol.*, Vol. II (1894), pp. 66–100.

[3] "La Notion de profil d'équilibre," *Compt. rend. Congrès internat. géog.*, Vol. III (1926), p. 61.

ORIGIN OF THE NOTION OF BALANCE OR EQUILIBRIUM IN RIVERS

The writings of most geomorphologists who have investigated the question of balance in the work of streams acknowledge the influence of the studies of French hydrologic engineers of the middle of the last century, particularly Surell and Dausse, and also of Gilbert. Dausse and Baulig have pointed out that Italian engineers developed similar ideas prior to the French, but their influence upon present-day geomorphology is limited to the few quotations incorporated into the writing of Dausse. The studies of Surell, Dausse, and Gilbert can thus be credited with having provided the major basis for the notion of grade in rivers. A review of the statements of these three men, relative to the subject, therefore becomes imperative and will be given precedence over Davis' treatment of the question.

ALEXANDRE SURELL

Surell's ideas are contained in his classic *Etude sur les torrents des Hautes-Alpes*,[4] which has had a lasting influence upon geomorphology, especially in France. The following passages of the study are of particular interest in the present discussion:

> A careful study of the courses of the torrents . . . . leads to the recognition of three parts, which are clearly defined by their form, by their position, and by the constant effects which the water achieves in each of them. First, an area in which the water collects, and excavates the terrain. . . . . Then another area, in which the water deposits the material derived from excavation. . . . . Finally, between the two areas, a third, in which the transition from excavation to accumulation takes place. . . . . [It is] a section of varying length, through which the water passes without deepening the channel and without raising it . . . . in which there is no more erosion and where deposition does not yet start. I shall call it the *runoff channel*. This is the least well defined among the three parts and, nearly always, the shortest. . . . . The runoff channel is always held by two well-defined banks. As a matter of fact, were the banks missing, nothing would prevent the torrent from leaving its bed; it would lose its velocity and would deposit.[5]

[4] 1st ed., Paris, 1841. The following quotations were translated from the 2d ed. of 1870. The translations are not literal. They are, therefore, correct with regard to meaning but are not identical with the French original in word order and sentence structure, a fact which necessitated occasional changes in words.

[5] *Ibid.*, pp. 13–17.

Surell suggests that the longitudinal profile of the bed of a torrent be drawn together with the height of the adjoining slopes and the elevation of the plain upon which the torrent issues and remarks:

> This will be a diagram in which one may read with perfect clearness the nature of the action which the torrents perform upon the terrain in the different parts of their courses. Mountainward the curve of the terrain rises above that of the torrent bed; valleyward, it falls below. The two curves consequently have to intersect, and this point of intersection marks the passage from downcutting to upbuilding. It is located at the mouth of the gorge and at the apex of the alluvial cone.[6]

Only one map of a typical torrent accompanies Surell's book.[7] The collecting basin and the alluvial cone of the torrent stand out clearly on this hachured map and seemingly also the middle sector, the runoff channel, comprising about one-quarter of the total length of the torrent. Reference to the legend reveals, however, that what one assumes to be the middle sector is only the lower part of the catchment basin, called the "bottleneck" (*goulot*). The legend then informs one that the runoff channel is located at the apex of the alluvial cone but is too short for representation.

Comparing rivers with torrents, Surell then declares:

> The flow of water in the bed of a torrent follows the same laws as in the bed of the largest rivers. . . . . Torrents thus do not display phenomena which differ from those encountered in the largest streams. . . . . The fundamental attributes, to excavate, to transport, and to deposit, belong to all streams. . . . . What happens at the mouth of rivers when they meet the level of the sea is directly comparable to what happens in torrents emerging onto plains; the deltas are true alluvial cones. . . . . On the other hand, rivers would not have deltas, if they did not arrive loaded with detritus which they obtained in the upper parts of their courses. They have thus also their collecting basins where they excavate. Their two extremities thus end like those of torrents. But the intermediate part, that is, the runoff channel, which is nearly nil in torrents, by itself constitutes nearly the full course of rivers.[8]

Of importance also is Surell's "limiting gradient," presented as follows:

> In some [torrents] . . . . the slopes of the alluvial cone join the gradient in the gorge tangentially. . . . . In others, on the contrary, the curve of the bed shows here a more or less abrupt break [where the steep gradient of the gorge meets the gentle gradient of the cone]. . . . . One also finds that in torrents of

[6] *Ibid.*, p. 23. [7] *Ibid.*, Pl. I. [8] *Ibid.*, pp. 24–25.

the first type the inclination of the alluvial cone is such that the material brought down would be washed to the [trunk] river, if the water did not spread it by leaving its bed. This fact can be verified by comparing this inclination with that of other torrents which, transporting the same kind of material, do not deposit any more, solely because they can no longer leave their bed, either on account of certain work of man or through the effect of natural events. Moreover, one realizes that such a slope must exist for all types of material; we shall call it the limiting gradient (*pente-limite*). . . . . [Torrents of the second type] offer examples of beds in which the curve [of the longitudinal profile] is not yet completely attained. The gradients are imperfect, and the formation is incomplete. It can readily be foreseen that in such torrents upbuilding [of the alluvial cone] must take place in a most energetic fashion, while the same action in those of the first type is already entirely completed.[9]

Impressive is the sight . . . . of an alluvial cone of a former torrent . . . . covered with woods, cultivated fields, and frequently also habitations. . . . . A little brook . . . . issues from the gorge and quietly traverses the fields; this brook formerly was the torrent. . . . . It has entrenched itself in its own alluviations between deep banks covered with succulent grassland. . . . . It must thus be admitted . . . . that the violence of the torrents is not indefinite in its duration. . . . . Finally, there are torrents which by their form and effects assume an intermediate position between extinct and fully active torrents. They are not yet entrenched in a stable fashion amidst their deposits, but they spread only over a small part of their cone. The rest is covered with fields, woods, houses, and appears to have been abandoned by the torrent since time immemorial. All kind of intermediate stages illustrate this transition which starts with the establishment of the limiting gradient and ends with the most complete extinction.[10]

The action of torrents may thus be divided into three periods, corresponding to three ages, in each of which aim and effects are different.

The first period embraces the creation of the [longitudinal] curve of the bed.

During the second the curve is created, but the course is not yet fixed. It is characterized by the presence of the limiting gradient as well as by divagations [of the course].

The third period finally corresponds to the establishment of a stable regimen.

Resuming the parallelism [between torrents and rivers], I see in all streams three successive periods [of development].

1. A period of *corrasion and upbuilding* which prepares the bottom of the valley and everywhere distributes gradients which bring an equilibrium between the resistance of the ground and the friction of the water. It endeavors to fix the longitudinal profile of the stream.

2. A period of *divagation*, whereby the water seeks the form of section and the

[9] *Ibid.*, pp. 25–26. [10] *Ibid.*, pp. 135–40.

bends which correspond to the greatest stability; for the straight course is not always also the most stable, firstly because it has a steeper gradient, and secondly because it does not necessarily lead the current toward the points where the bank is the most solid. The action of the water is restricted to the shifting of a badly defined bed within one and the same plane, without noticeable wear or accretion of the bottom [of the valley]; it is the liquid mass rather than the ground which changes location. The result of this second period consists in fixing the alignment of the course, or, in other words, in determining its plan.

3. Finally, a period of *regimen*, during which the water overflows and returns into an invariable bed.[11]

M. DAUSSE

This French engineer investigated the work of rivers and torrents from the very practical viewpoint of flood control and bridge-building and studied especially the effect of engineering structures upon the work of streams.[12] He recognized that all corrective work of man on streams, such as straightening the course, confinement between levees for limited or extensive stretches, filling along one of the banks, change of course forcing a settlement of debris in lakes, and construction of bridge pillars, buttresses, or jetties, caused marked changes in river work. Modifications of discharge, velocity, width, depth, and gradient of the river bed which result often nullify the efforts of hydraulic engineers to control river work. Seeing that these changes occurred soon after construction and were followed by apparent stability, he was led to reaffirm Surell's law of equilibrium. Dausse, furthermore, visualized its applicability to slopes as well, stating:

> This formula: The gradient of the stream and the form of each of its sections are the result of an equilibrium between the force of the current and the resistance of the materials of the river bed, expresses not only a hydraulic axiom. The forms of solids which suffer attack from atmospheric agents also follow from it; they are also the result of an equilibrium between the forces which endeavor to carry off the particles of these solids and the forces which hold them back.[13]

Noteworthy are the three factors which Dausse held to be of major importance in causing increased erosion of corrected streams in alluvial deposits, viz., straightening of the course, narrowing of the channel, and purification.[14] The last-named cause serves to ex-

[11] *Ibid.*, pp. 145–49.

[12] Dausse, "Etudes relatives aux inondations et à l'endiguement des rivières," *Institut de France: mémoires présentés par divers savants à l'Académie des sciences*, Vol. XX (1872), pp. 287–507.

[13] *Ibid.*, p. 321.

[14] *Ibid.*, p. 325.

plain Surell's uninterpreted observation that extinct torrents traverse their cones in marked entrenchments eroded despite reduced discharge.[15]

G. K. GILBERT

Gilbert's discussion of stream work is contained in his classic *Geology of the Henry Mountains*.[16] While the interest of the French hydrologic engineers had mainly been directed toward the harnessed, ineffective river, the American geologist saw in streams a major force in land sculpture. This difference in interest led to a difference in stresses. The engineers looked for the equilibrium between friction and velocity which would assure stability of the river bed. Gilbert's equilibrium is, in his own words, an equilibrium of action. While the interest of the engineers was focused upon the destructive effects of rivers, the geologist was more interested in the rivers' share in modifying land forms, and his discussion centers upon transporting power, load, and erosive power.

Gilbert's equilibrium of action refers to a corrading stream of constant volume traversing a succession of hard and soft rocks, creating gentle reaches in soft material and declivities in resistant rocks. Gilbert asserted that the differentiation of gradients will not progress indefinitely but only

> . . . . until the capacity for corrasion is everywhere proportioned to the resistance, and no further,—that is, until there is an equilibrium of action.[17]

This principle—Gilbert's law of structure—has found little application in subsequent physiographic literature.

Of greater importance, especially to the development of the concept of grade in streams, were his discussions of the relations of power, load, and corrasion. The power of a stream, conditioned by volume and slope, is used partly in the movement of the water, partly in the transportation of debris, and the rest in corrasion.

> Where a stream has all the load of a given degree of comminution which it is capable of carrying, the entire energy of the descending water and load is consumed in the translation of the water and load and there is none applied to corrasion. . . . . A fully loaded stream is on the verge between corrasion and depo-

[15] *Ibid.*, p. 338.

[16] *Report on the Geology of the Henry Mountains* (Washington: U.S. Geographical and Geological Survey of the Rocky Mountain Region, 1877).

[17] *Ibid.*, p. 113.

sition. . . . . It may wear the walls of its channel, but its wear of one wall will be accompanied by an addition to the opposite wall. The work of transportation may thus monopolize a stream to the exclusion of corrasion.[18]

It has been shown in the discussion of the relations of transportation and corrasion that downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. The first result of the wearing of the walls of a stream's channel is the formation of a flood-plain. As an effect of momentum the current is always swiftest along the outside of a curve of the channel, and it is there that the wearing is performed; while at the inner side of the curve the current is so slow that part of the load is deposited. In this way the width of the channel remains the same while its position is shifted, and every part of the valley which it has crossed in its shifting comes to be covered by a deposit which does not rise above the highest level of the water. The deposit is of nearly uniform depth, descending no lower than the bottom of the water-channel, and it rests upon a tolerably even surface of the rock or other material which is corraded by the stream. The process of carving away the rock so as to produce an even surface, and at the same time covering it with an alluvial deposit, is the process of *planation*.[19]

Gilbert also realized that the load carried by a stream is very instrumental in the erosive process:

The mechanical wear of streams is performed by the aid of hard mineral fragments which are carried along by the current. The effective force is that of the current; the tools are mud, sand, and bowlders. . . . . Streams of clear water corrade their beds by solution.[20]

The growth in erosive efficiency of a stream with increase in load does not progress unchecked:

The blows which the moving fragments deal upon the stream-bed . . . . are increased in number up to a certain limit by the increase of the load of the stream; but when the fragments become greatly crowded at the bottom of a stream, their force is partially spent among themselves, and the bed-rock is in the same degree protected.[21]

Noteworthy also is Gilbert's discussion of the mechanics of transportation:

The friction produces inequalities in the motion of the water, and especially induces subsidiary currents more or less oblique to the general onward movement. Some of these subsidiary currents have an upward tendency, and by them is performed the chief work of transportation. They lift small particles from the bottom and hold them in suspension while they move forward with the

[18] *Ibid.*, p. 111. [19] *Ibid.*, pp. 126–27. [20] *Ibid.*, p. 101. [21] *Ibid.*, p. 112.

general current. The finest particles . . . . are carried farthest before they fall. Larger ones are barely lifted, and are dropped at once. Still larger are only . . . . rolled over without quitting the bottom . . . . and the largest fragments are not moved at all.[22]

Of interest is also Gilbert's view concerning the relation between capacity and supply:

The rate of transportation of débris of a given fineness may equal the capacity of the transporting stream, or it may be less. When it is less, it is always from the insufficiency of supply. The supply furnished by weathering is never available unless the degree of fineness of the débris brings it within the competence of the stream at the point of supply.[23]

WILLIAM MORRIS DAVIS

The geological viewpoint of Davis determined his preference for Gilbert's balance between power and load to the French engineers' equilibrium between the force of the current and the resistance of the bed, as the latter concept omits any consideration of the load. At the suggestion of Gilbert, Davis then introduced the name of "graded river" for a stream with capacity load. Gilbert's thesis that the fully loaded stream erodes laterally and thus creates flood plains was found satisfactory and was adopted. Surell's three stages in the development of rivers reoccur in Davis' geographical cycle. Grade is attained at the end of the first stage, according to both authors. Davis, however, also considered the ramifications of a stream system:

When the trunk streams are graded, early maturity is reached; when the smaller headwaters and side streams are also graded, maturity is far advanced; and when even the wet-weather rills are graded, old age is attained.[24]

Davis extended the principle of balance between power and load to the development of slopes, thereby surpassing Dausse, who only asserted the possibility of application:

When the migration of divides ceases in late maturity, and the valley floors of the adjusted streams are well graded, even far toward the headwaters, there is still to be completed another and perhaps even more remarkable sequence of systematic changes than any yet described: this is the development of graded

[22] *Ibid.*, p. 106. [23] *Ibid.*, p. 110.

[24] "The Geographical Cycle," *op. cit.*, pp. 258–59. Originally published in *Geog. Jour.*, Vol. XIV (1899), pp. 481–504.

waste slopes on the valley sides. . . . . A graded waste sheet may be defined in the very terms applicable to a graded water stream; it is one in which the ability of the transporting forces to do work is equal to the work they have to do. . . . . From any point on such a surface a graded slope leads the waste down to the streams. At any point the agencies of removal are just able to cope with the waste that is there weathered plus that which comes from farther uphill.[25]

Gilbert's assertion that downward corrasion ceases in a fully loaded stream was obviously in opposition to Davis' assumptions of maintenance of grade in rivers from maturity into old age and of continuance of the erosive lowering of stream beds after maturity, a prerequisite of peneplanation. The following consideration served to dispose of the difficulty:

It is too often implied . . . . that when a river is once balanced between erosion and deposition its slope thenceforward remains constant. . . . . When a stream is first graded, its channel is not level, and it has not reached the base of its erosive work. In virtue of the continual, though slow, variations of stream volume and load through the normal cycle,[26] the balanced condition of any stream can be maintained only by an equally continuous, though small, change of river slope, whereby the capacity to do work, and the work to be done, shall always be kept equal. It might at first be thought that changes of this kind would be perceptible, and that there would be occasional departures of a river from the graded condition, but such is not the case, because the change in the value of any variable in a unit of time is only by a quantity of the second order, by a differential of its total value. Once graded, a river will never depart perceptibly from the graded condition as long as the normal advance of the cycle is undisturbed.[27]

CRITICAL EVALUATION

Surell's law of equilibrium in stream work has some bearing upon the concept of the graded river, although it neglects consideration of the load. It is postulated that the balance is achieved only between the friction of the water and the resistance of the bed. The

[25] *Ibid.*, pp. 266–68.

[26] In other essays Davis explains that these slow variations in stream volume and load consist in (*a*) a decrease of precipitation which is caused by the wearing-down of the highlands, (*b*) a retardation of runoff resulting from the accumulation of waste on the constantly flattening slopes, and (*c*) a decrease in load caused by the decrease in precipitation, the retardation of runoff, and the decrease in velocity resulting from the decreasing declivity of all slopes.

[27] Davis, "Base-Level, Grade, and Peneplain," *op. cit.*, p. 398. Originally published in *Jour. Geol.*, Vol. X (1902), pp. 77–111.

attainment of such a balance, in which the resistance of the bed would compensate the frictional attack by the water, would obviously mean the end of all erosion and is usually interpreted in this fashion. Nothing definite concerning the opposite process in river work—deposition—can be deduced from the postulate, as load is not included in it. It would not thus necessarily imply stability of the river bed but only absence of erosion.

This condition of balance is claimed to be reached with the attainment of the limiting gradient. The presentation of the latter, quoted above, indicates by the approach from the viewpoint of deposition that this limiting gradient is one of deposition. It is that gradient of the alluvial cone which has reached a sufficient steepness to prevent further deposition and thus forces the torrent to carry all the load to the trunk river. This concept of limiting gradient corresponds therefore to Gilbert's concept of balance between power and load and Davis' concept of grade in streams. Surell assures us that the law of equilibrium governs the flow in streams which have acquired this limiting gradient but makes no attempt to prove his contention. If true, this law of equilibrium would definitely eliminate all possibility of erosion by a graded stream. Surell's combination of the limiting gradient with the state of equilibrium, however, remains only a postulate which appears inspired by the desire for stability of river beds, attainable only if erosion as well as deposition is lacking. In this combination the law of equilibrium would guarantee absence of erosion, while the limiting gradient would assure absence of deposition.

The proof of graded conditions in streams appears to lie in the presence of a middle sector in which the transition between erosion and deposition takes place. A critical study of Surell's statements relating to this middle sector, or runoff channel, shows them to be quite contradictory. We are assured that this sector is clearly defined, even in torrents, but read later that it is nearly nil. Consistent with the latter statement is Surell's admission that it could not be represented on the map of the typical torrent. The discussion of the diagram in which terrain and torrent course are plotted together indicates that this middle sector is practically nil, a point. The empirical description of the runoff channel also raises skepticism. It is

stated that high banks prevent overflow and deposition by the torrent in this sector. Frequently this part of the torrent is referred to as a gorge. The middle sector thus occupies a cut of definitely erosive origin. Nothing warrants the conclusion that erosive action in this sector is something belonging to the past. The evidence also allows the interpretation that the ideal torrent remains erosive to the very mouth of the gorge by which it issues onto the plain. Below that point deposition is the rule. Shrinking to a point, the middle sector can obviously not be shown pictorially as a sector, either on the map or on the profile of the torrent; it is less than "nearly nil"—it is nil.

The fact of the perfect balance between power and load for this single point is of great interest to engineers, since it approaches the ideal condition of a nearly inoffensive stream. It is thus not surprising that an engineer suggested this condition of balance as a working hypothesis which should guide future corrective work on streams and that other engineers proclaimed it to be a hydrologic axiom. It is only unfortunate that many morphologists accepted this working hypothesis as a law governing the work of streams in nature, although other investigators recognized the misconception and either eliminated the transitional zone between erosion and deposition, as, for example, A. de Lapparent[28] and Hermann Wagner,[29] or pictured it as a zone in which erosion and deposition alternate, as, for example, Albrecht Penck,[30] Eduard Brückner,[31] and Fritz Machatschek.[32]

Surell's inability to show the presence of a graded middle sector for torrents also deletes his assumption of an extensive graded middle sector in rivers.

While no objection can be raised to Surell's attempt to divide the

[28] *Traité de géologie* (Paris: F. Savy, 1883), pp. 187–89. The editions of 1900 and 1906 show no change in this section.

[29] *Lehrbuch der Geographie*, I Bd., 2. Tl. (Hanover: Hahn, 1922), p. 332.

[30] *Morphologie der Erdoberfläche* (Stuttgart: J. Engelhorn, 1894), p. 322.

[31] *Die feste Erdrinde und ihre Formen* (Prag and Wien: F. Tempsky; Leipzig: G. Freytag, 1897), p. 223.

[32] "Die Arbeit des fliessenden Wassers," *Supan-Obst, Grundzüge der physischen Erdkunde*, Bd. II, Tl. 1 (Berlin and Leipzig: Walter de Gruyter & Co., 1930), p. 190.

development of torrents and streams into three parts, dissatisfaction can be expressed regarding the principle of division. The differentiation of torrents into varied ages refers only to their actions on the alluvial cones and remains incomplete even on this point, since it omits consideration of erosion in their last stage. Extension of the same criteria with little modification to the major part of the courses of the rivers leads to a very unsatisfactory characterization of stages which has, to my knowledge, never been accepted.

The studies of Dausse provide nothing in support of the concept of grade or of Surell's law of equilibrium in stream work. The latter is accepted without criticism.

As lasting as Surell's influence upon French geomorphology is Gilbert's influence upon American physiography. The notion of the stream loaded to capacity is commonplace. Accepted also are his assertions that a capacity load prevents downward corrasion of a stream without impairing lateral corrasion, that a fully loaded stream can enlarge its meanders, that the sweeping of the meanders of a fully loaded stream will create a flood plain, and that the same process may finally lead to the complete planation of an area.

The first assertion seems to result from the condition of balance between power and load of a fully loaded stream, which leaves no energy for corrasion. A logical application of the latter conclusion, however, would not only eliminate downward corrasion but sideward corrasion as well. Gilbert's suggestion that the load of a stream protects the bed from attack is not applicable to a stream loaded only to capacity, as such a stream will keep the full load in motion and thereby continue to attack bedrock with its blows. Neither lateral nor downward corrasion will therefore be stopped when a stream reaches the condition of grade. Of the two forms of attack, downward corrasion will be favored by the fact that most of the load is carried along the bottom of the bed.

This conclusion contradicts the supposition that in a graded river all energy is used for the movement of the water and the transportation of the load. As corrasion by the moving load cannot be denied, it follows that a fraction of the energy of the river is spent in erosion. A fully loaded stream will thereby lose energy which will first affect the velocity of part of the load and, through it, also of parts

of the stream, will thus decrease competence for the larger sizes and soon also the capacity for transportation, and will in this fashion lead to deposition. A graded stream can, therefore, not remain at grade unless the continuous loss in energy due to corrasion and the attendant increase in load are exactly counterbalanced by a similarly continuous increase in energy which could only result from acceleration of gravity. The presence of a slope permits admission of this possibility to a certain degree. The fully loaded stream could possibly continue to carry its load but would also remain an erosive agent.

FIG. 1.—Section of a river bed, filled to the rim, showing the shift of the bed necessary for the maintenance of the conditions of flow and of the load.

Since an underloaded and a fully loaded stream will erode, and since an overloaded stream will deposit, there remains no relationship between power and load which guarantees unchanged maintenance of the bed. It appears that streams have either to erode or to deposit but cannot assume a neutral position.

The further assertion that a fully loaded stream can displace its meanders is similarly untenable. The suggestion that the river could maintain the size of the load by dropping as much of it on one side as it picks up on the other could only be carried out by a stream which fills its bed to the rim (Fig. 1). Only in this case would the suggested exchange of load along the wetted surface be physically feasible. Difficulties are encountered already in this most favorable case. Gilbert rightly pointed out that the volume and the composition of the load of a stream depend upon the availability of debris in varied size groups. In order to maintain volume and composition of the load in the exchange and thus prevent morphological changes of the stream bed, it would be necessary that during the displacement of the meanders exactly the same sizes—gravel, sand, silt, clay—as are picked up on the outer bend were deposited on the inner bend and in exactly the same amount. No size resulting from the undercutting action of the stream should be above that which it is competent to move, as it would not be carried off, would change the cross section of the river, and would thereby affect the carrying

power and the magnitude of the capacity load. For the same reason it is necessary that the deposited material assume a compactness identical with that of the removed portion and, further, that removal and deposition be distributed in a manner which produces only a horizontal shift of the cross section. Against so many obstacles a trading of the load which would leave the stream at grade becomes at least highly improbable, if not directly impossible. No lengthening of the stream course could be associated with the displacement of the meanders, as this would automatically decrease the carrying capacity and would result in alluviation. A stream with a relatively straight course at the moment it reaches grade could not thus acquire meanders while maintaining grade. The irregular sinuosities of a youthful stream could not grow into smooth meanders of larger radii so characteristic of late maturity, if graded conditions were maintained.

FIG. 2.—River in a shallow cut. There is no space in the bed of the river to compensate for the addition of the slump *ABC* to the load by a commensurate deposition from the old load.

It can be speculated that the centrifugal force, or the piling of water on the outer bank, or the pendulation of the water surface through bends will create greater velocities and thereby increase the erosive and carrying capacities of the stream in bends, thus allowing for the corrasion of the outer bank and the removal of the increased load. This increase in power will be only temporary, however, and will be followed by a decrease in carrying capacity, forcing deposition in form of the familiar shoal between bends. The fully loaded stream would continuously carry the increase in load from the bend to the next shoal, raising the latter constantly, a morphologic change which could not continue without effects upon the carrying capacity of the stream and its ability to move its original load. The difference in action of streams in bends and over shoals raises doubt even in the possibility of maintenance of a full load in meandering rivers.

Sweeping of the meanders of a fully loaded stream will become impossible when the river banks rise considerably above the high-water level; that is, when the river occupies an erosional cut estabtablished prior to the attainment of grade (Fig. 2). The undercut-

ting action by the river will cause slumping of the riverbank. There is no space in the bed of the fully loaded stream to compensate the resulting increase in load by a commensurate settling from the old load. The mass of the slump will have to block the passage, and the fully loaded stream will never be able to remove the obstruction, because it is always loaded to capacity and is unable to increase its load.

Still greater difficulties beset the assumptions that a fully loaded stream flowing in an erosional cut will be able to form a flood plain through lateral corrasion and that it may accomplish lateral planation of extensive areas. The large volume of material which the fully loaded stream would have to remove in either case (*ABCD* in Fig. 3) could never be compensated by dropping of part of the older load in the river bed. The greatest amount the stream could deposit without raising its bed would correspond to a layer equal in thickness to the greatest depth of the river (*ABEF* in Fig. 3). The difference between the volume postulated to be eroded by the river and that deposited within the bed of the sweeping river (*FECD* in Fig. 3) would have to be carried away by the fully loaded stream, again a feat it could not accomplish, as it enters the area loaded to capacity and is unable to acquire additional load.

FIG. 3.—Planation would demand removal of *ABCD*, compensated at best by deposition *ABEF*. The mass *FECD* would have to be carried away by the river.

Davis' difficulty of combining grade with erosion is overcome by the reasoning offered above, that even a fully loaded stream will erode as long as it remains able to move all its load. This solution, however, offers no proof for the postulate that mature and old rivers are always at grade. The graded stream but shares ability to erode with streams which are not loaded to capacity.

Davis' assertion that slopes also will become graded is as doubtful as the condition of grade in rivers.

The critical review leads thus to the following conclusions.

1. The presence of a middle sector in torrents and rivers, in which

power and load are balanced and neither erosion nor deposition occurs, could not be shown by Surell.

2. Gilbert's assumption that downward corrasion ceases with the attainment of a full load and is replaced by lateral corrasion is in error. Both forms of corrasion could continue in spite of a capacity load acquired by a stream.

3. Meandering streams, loaded to capacity, cannot shift their meanders, since volume and composition of the load and the shape of the cross section could not be maintained in the process.

4. Fully loaded streams could not create flood plains by lateral erosion or accomplish planation of extensive areas by the same process, since although competent for erosion, they are incompetent for the necessary removal of debris.

APPEARANCE OF A FULLY LOADED STREAM

A fully loaded stream is a mixture of water and debris. Many are the gradations between a clear brook in which only occasionally a traveling particle may be seen and the mass of moderately lubricated debris involved in a landslide. Where in this scale is the position of the stream loaded to capacity? The amount of load which a stream can acquire will vary with the velocity of flow. With extremely low velocities a clear brook may represent the fully loaded water course, while with higher velocities a considerable turbidity can be expected. But the load also affects the velocity of a stream, decreasing it with increased internal and external friction. A capacity load should have very marked effects upon velocity. Relatively small velocities should, therefore, be characteristic of fully loaded streams. Of considerable interest in this respect is the comparison of an extremely muddy stream with a true mudflow, which may both occur in the same stream channel. Which of the two represents the fully loaded stream? The load of the slowly moving mudflow is obviously larger with respect to the associated water than the load of the muddiest stream. The mudflow would thus represent the fully loaded stream. Objections will immediately be raised that the true mudflow is not a stream. But may not the condition of a full load also change the characteristics of movement and transform the rapid stream into a slowly moving flow?

The concept of the fully loaded stream appears thus quite elusive and to escape accurate determination in nature in spite of the ease with which it can be defined.

THE GRADED STREAM AND FLOODS

One of the many prerequisites of the graded stream is the condition of constant discharge. But this is never attained in streams, owing to the erratic occurrence of precipitation and the great variability in depth and rate of precipitation of individual storms. Temperature and humidity of the air and the ground, type of plant cover, lithology, and snow and ice further influence runoff. The lack of constant discharge in streams renders the maintenance of graded conditions an all too obvious impossibility. The observable efficiency of floods in stream work has led to the conclusion that times of flood are the major, if not the only, periods of modification of the stream bed and that the balanced stream profile characteristic of graded conditions developed during these periods.[33] This amounts to an admission that streams are not graded at other times. They could, therefore, be erosive agents also at times of low discharge. Remembering that discharge below flood stages prevails during the greater part of the year, one might claim that very large erosive changes might be accomplished during these periods of ungraded conditions. Surell's description of the alluvial cones of extinct torrents can be cited as proof that decrease in discharge really will increase erosive efficiency. During the last stage of development the torrent changes to a brook and, in spite of decreased volume, cuts a trench into the deposits which the more powerful torrent formerly could not dissect.

The conclusion that floods will create a graded stream profile is also incorrect. There is no uniformity among the floods of a stream, either as to duration, maximum height, or rate of increase and decrease in discharge, as the differentiation of floods by the year of their occurrence clearly shows. In large stream systems different areas receive the varied amounts of excessive precipitation which cause the individual floods. Coupled with the highly variable factors which determine the associated runoff, a great variety of flood discharges in the main river will result which can only lead to similarly

[33] Baulig, *op. cit.*, p. 59.

varied morphological effects. The great variation in action of the individual floods cannot lead to the development of a longitudinal profile with a gradient which would allow maintenance of balance between power and load during each individual flood. A profile with gradients suitable to one flood would be highly unsuitable to the following flood. Each flood modifies the gradients of the stream bed according to its specific conditions of volume, rate of increase and decrease of discharge, availability of load, etc. There thus appears to be no time in the life of a stream during which graded conditions are attainable, either for the full length or along a large sector of its course.

The work of streams seems rather to be a constant action, varying with the factors which determine its intensity and character. Stages of high, middle, and low water are associated with erosion, transportation, and deposition. Some areas undergo erosive attack at all times, others show the effect of continuous deposition, but for most of the length of the stream courses both actions are carried out simultaneously or successively, varying in intensity with variations in discharge. The net result may at one time swing toward erosion; at another, deposition may dominate at the same point. Flood deposits are dissected when the discharge decreases; the channel produced during average discharge may be deepened by floods or filled with deposits. Transportation also is a constant process, varying similarly in intensity. There is no place for absence of action or uniformity of action as postulated by the concept of grade.

IMPROBABILITY OF A FULL LOAD IN RIVERS

The total volume of the load of a stream does not depend merely on the inherent energy of the moving water; it is also conditioned by the availability of sizes of debris transportable by the stream. This conditions the difference between the generally clear though rushing mountain streams and the usually turbid though languid flood-plain streams, or the contrast between the milky creeks issuing from glaciers and the clear water of the creeks from near-by unglaciated areas, or the difference in turbidity between streams from areas of shale or fissile schists and streams from granitic or calcareous regions. As very turbid or muddy streams are relatively infrequent, it ap-

pears that the condition of a full load is at best only infrequently attained. The assertion that all mature streams are always fully loaded clearly shows disregard of the lithological conditions which affect the load in streams.

Gilbert's account of stream work, quoted above, displayed a marked realization of the influence of turbulence in the transportation of debris. Subsequent studies[34] have confirmed the importance of turbulence in transportation. Turbulence originates in the varied velocities which at any moment are found in juxtaposition in any part of a stream. The changes in values and in distribution of velocities from one stream section to another are obviously associated with corresponding changes of turbulence. A brief observation of one section of a stream will reveal that within it turbulence changes continually. These constant variations in turbulence must cause continuous modifications of the carrying power of a stream and with it of the load. Adjustments through dropping of part of the load will be easier than the opposite process, as the picking-up of a particle against gravity demands a greater force than is necessary to keep it moving.[35] For this reason a force which does not reach the necessary magnitude will be unable to increase the load and will not be fully utilized in transportation, spending itself partly in friction. Similarly, a turbulent impulse of sufficient magnitude to lift a certain size of debris will again not be applied to transportation, if no particle of that or of a more erosible size is available at the point where the turbulent movement occurs. As turbulence can be seen to arise re-

[34] Gilbert, "The Transportation of Débris by Running Water," *U.S. Geol. Surv. Prof. Paper 86* (1914); John B. Leighly, "Toward a Theory of the Morphologic Significance of Turbulence in the Flow of Water in Streams," *Univ. Calif. Pub. Bull. Dept. Geog.*, Vol. V (1932), pp. 1–22; and "Turbulence and the Transportation of Rock Débris by Streams," *Geog. Rev.*, Vol. XXIV (1934), pp. 453–64.

[35] Georg Strele, in *Grundriss der Wildbachverbauung* (Wien: J. Springer, 1934), p. 51, states that, after transportation has been initiated, the hydraulic force may decrease by about 30 per cent before redeposition takes place.

Filip Hjulström, in "Studies of the Morphological Activity of Rivers as Illustrated by the River Fyris," *Bull. Geol. Inst., Upsala*, Vol. XXV (1935), pp. 221–527, found that, for particles of 7 mm. and above, the maximum velocities permitting deposition of the different sizes were 29 per cent below the minimum velocities necessary for erosion of unconsolidated deposits of debris of equal sizes. For smaller sizes of the particles the difference in velocities is even larger, increasing to 99 per cent for silts and clays which are transportable at practically any velocity. Reference on pp. 320–24.

peatedly at the same point, which is thus quickly cleared of the favorable sizes, this form of loss of turbulent energy to transportation must be common. Turbulent energy which does not reach to the source of supply of debris will also be unable to increase the load. The marked turbulence which originates near the surface of rivers and penetrates only a short distance downward is, therefore, in the main unavailable to transportation.[36] With so many handicaps to the acquisition of the load and none to its deposition, it becomes quite impossible to visualize the attainment of a full load in a stream and to imagine maintenance of a stable load during the process of trading. Furthermore, the constant changes in turbulence from point to point and the repeated variations in turbulent activity at one and the same point indicate that the hydraulic power does not remain uniform—another handicap to the continued transportation of a uniform load. Comparison of the distribution of turbulent energy with the distribution of sediments in a stream cross section gave Leighly "the impression that the middle depths of streams are normally unsaturated."[37] The same author also states that Humphreys and Abbot arrived at the same conclusion in their classic study of the Mississippi. It has, therefore, to be concluded that all streams, in all their sections and at all times, carry a load below their capacity.

ADVANTAGES RESULTING FROM THE ABANDONMENT OF THE CONCEPT OF GRADE IN STREAMS

It was shown in a preceding section that under favorable but probably exceptional conditions of gradient even the ideal graded river could remain an erosive agent, but probably only one of a very minor order of efficacy. The fact brought out subsequently that even mature and old streams are always underloaded makes their continued erosive efficiency leading to general peneplanation much better understandable. Davis' efforts to reconcile grade with erosion amounted to a partial admission that the great erosive task remaining after maturity is incompatible with the postulate of maintenance of balance between power and load.

The logical application of the concept of grade in rivers also elimi-

[36] Consult Fig. 1*b* in Leighly, "Toward a Theory . . . . ," *op. cit.*, p. 7.

[37] *Ibid.*, p. 16.

nates the formation of flood plains through alluviation by graded rivers. Such rivers, capable of continued transportation of their entire load and devoting themselves fully to the discharge of this task, will not deposit any part of their load on flood plains. Alluvial plains thus find scant consideration in the river-valley cycle in which the normal flood plain is treated as an erosional feature, that is, the planed surface which the graded river is supposed to create through lateral corrasion. The alluvial cover of this feature is only incidental, resulting solely from deposition within the shifting stream bed. Neither deposits of floods nor natural levees belong to this feature. The other outstanding alluvial feature—the delta—is similarly excluded from the cycle, as it would disrupt the maintenance of graded conditions by extending the course. A. K. Lobeck[38] thus treats delta formation as modification of the river cycle and reasons that it will cause alluviation to the very headwaters of a river. Neither deltas nor flood plains should thus be divorced from the development of rivers and their valleys. If no attempt is made to maintain the impossible graded condition of a river, high- and low-water stages with their associated variations in erosion and deposition can be given due recognition, and flood plains and deltas become requisite parts of river valleys. The all too abstract nature of the river-valley cycle is thereby conveniently modified to comply better with the observable forms.

The renunciation of the concept of grade in rivers also would promote a greater interest in river action and should ultimately lead to a better understanding of the processes associated with the work of streams.

The discontinuance of the concept of grade also would lessen interest in the profile of the graded or balanced river—a profile for which the representative stream has also not yet been found. The factors which are of real importance in the development of the longitudinal profile, such as marked differences in lithology, the erratic increase in hydraulic power associated with the sudden increase in volume of rivers through junction of tributaries, and seasonal variations in stream flow and load, can then be given proper consideration.

[38] *Geomorphology* (New York: McGraw-Hill Book Co., Inc., 1939), pp. 164–65.

MODIFICATIONS MADE NECESSARY BY DISCONTINUANCE OF THE CONCEPT OF GRADE IN RIVERS

Meanders cannot be understood as the result of a full load. In order effectively to prevent downward erosion and encourage lateral corrasion, a secure protection of the bed from attack is necessary, which can only be provided from the load of the stream. Meandering thereby becomes the result of alluviation. The two processes have long been associated. Meanders belong to flood plains. Even incised meanders are usually linked to flood plains; where they are numerous and well developed, they are interpreted as having originated on a former flood plain. However, instead of deriving meanders from alluviation, the opposite relationship was preferred, that is, the flood plain has been explained as the result of meandering. This interpretation has to be reversed and the meanders have to be recognized as the result of alluviation, following R. J. Russell's recommendation.[39]

The postulated efficiency of lateral erosion in meandering streams, usually regarded as a prerequisite for the widening of mature valleys has been overrated. Erosion can by no means be pictured as acting only laterally and not downward. Turbulence acts in many directions but was found by Leighly to be concentrated in two areas near the bed of a stream,[40] an arrangement which serves to minimize the postulated relative efficiency of lateral erosion. The turbulent energy of flood-plain streams finds, furthermore, quicker achievements in their own alluviations than in an attack of the bedrock of the valley sides. Meander bends can be seen to lose their regularity of shape and to include straight segments along bedrock outcrops and even along slopes of unconsolidated material frequently enough to suggest inefficiency in lateral attack. The natural levees which rivers construct in their flood plains will, following floods, occasionally favor a relocation of the course along one or the other side of the valley a position which might be interpreted to indicate a tendency of the stream to widen its valley. But by the same process of deposition leading to a natural levee the river will be shifted away from that

[39] "Physiography of Lower Mississippi River Delta," *Bull. La. Geol. Surv. Dept. Conserv.*, Vol. VIII (1936), p. 123.

[40] "Turbulence and the Transportation . . . . ," *op. cit.*, p. 463.

side of the valley toward another location in the flood plain long before the lateral wear of the stream will show any appreciable effect. The depositional features of flood plains are too evident to permit doubt of their alluvial origin. The widening of the valley bottom during maturity thus cannot be credited solely to erosive action of the stream but must be understood as the combined effect of the retreat of the slopes, of alluviation, and of lateral wear by the river.

As the shifting of meanders cannot account for the formation of flood plains, the process of planation of extensive areas by lateral erosion of streams appears even less possible. D. W. Johnson's explanation of the origin of rock pediments of desert regions through lateral planation[41] has, therefore, to be supplemented by due consideration of weathering and alluviation in the formative process, following Andrew C. Lawson's interpretation of these features.[42]

The picture of the graded river is invoked with particular frequency in physiographic descriptions of regions. In common usage of the term the postulate of balance between power and load is scarcely recalled. Instead, the term is understood to indicate the absence of waterfalls and rapids, a connotation more in harmony with the term itself. With this restricted and simply descriptive meaning of having a relatively smooth gradient, the notion of the graded river is still worthy of retention. This change in definition will affect the presentation of the geographical cycle only beneficially. Salisbury and De Martonne have long taught the cyclic development of land forms without ever accepting Davis' concept of balance between power and load.

The conception that slopes also become graded has similarly to be discarded. In its formulation by Davis, as quoted in a preceding section, this condition of grade does not quite correspond to the notion of grade in rivers, as it is claimed that for a point in midslope the agencies of removal will be able to cope not only with the waste that comes from further upslope but also with the material weathered at that point. Continued degradation of the slopes is thereby more effectively assured. The postulate of balance between weather-

[41] "Rock Planes of Arid Regions," *Geog. Rev.*, Vol. XXII (1932), pp. 656–65.

[42] "The Epigene Profile of the Desert," *Univ. Calif. Dept. Geol. Sci. Bull.*, Vol. IX (1915), pp. 23–48.

ing and removal, however, is no more tenable in this case than it is in the case of the graded river. On slopes the agencies of removal will also carry off less than they are able for the exact reasons stated in the discussion of transportation in streams.

The concept of grade on slopes also sheds little light on the processes which actually take place on them and is thus of little help in understanding their development. Investigations along the lines started by Otto Lehmann,[43] Walther Penck,[44] Sieghard Morawetz,[45] and others are much better suited to give an insight into the development of these features.

CONCLUSIONS

Balance between the power of a stream and its load is maintained, neither during floods nor during stages of low water, neither along the entire length of a stream nor along limited stretches, neither in youth, maturity, nor old age. River action consists of a combination of erosion, transportation, and deposition, all three of which are likely to take place simultaneously in any river section. The magnitudes of each process and of their sum vary considerably in time and space in accordance with the great variations which the many determining factors undergo.

The notion of balance between power and load has to be divorced from the customary picture of a graded river as a stream without waterfalls and rapids. With this limitation the concept of the graded river still remains highly useful but only for purely descriptive purposes. In this modified form it will still remain the major criterion of approaching maturity in the cyclic development of valleys.

Discarding the notion of balance between power and load of a river will be only beneficial for the understanding of the development of valleys, since it will allow due consideration of alluviation as a factor in the formation of valleys of an importance equal to that of corrasion.

Meandering, until now postulated to be a special form of cor-

[43] "Morphologische Theorie der Verwitterung von Steinschlagwänden," *Vierteljahrsschrift der naturf. Ges. Zürich*, Vol. LXXVIII (1933), pp. 83–126.

[44] *Die morphologische Analyse* (Stuttgart: J. Engelhorns Nachf., 1924), pp. 105–46.

[45] "Eine Art von Abtragungsvorgang," *Peterm. Mittl.*, Vol. LXXVIII (1932), pp. 231–33.

rasive activity of streams, can then be treated as what it is most frequently observed to be—a form of runoff associated with alluviation. Planation by lateral erosion alone will have to be discarded and the widening of valleys explained with due consideration of retreat of slopes and alluviation.

The mere assumption of graded conditions on slopes should be abandoned and be replaced by the results of an intensive study of the processes which govern the development of this most extensive of all features of the physical landscape.

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DEEP-ZONE DOME AND BASIN STRUCTURES

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ABSTRACT

A well-exposed area of gneisses was mapped in great detail. This mapping illustrates the processes of deep-zone deformation and reveals certain characteristic structures. Most characteristic is a dome and basin structure of any attitude. Application of the conclusions from small-scale mapping to areas of the pre-Cambrian complex indicates that many so-called batholiths are probably domal structures of paragneisses.

INTRODUCTION

A structure which is characteristic and perhaps diagnostic of deformation at great depths is a composite of unoriented domes and basins. Just as parallel open folds with axes in a horizontal plane are characteristic of deformation at moderate depth, so folds with nonparallel and nonhorizontal axes are characteristic of deformation at greater depths. One variation of these deep-zone folds is seldom recognized; it is the structure which fails in all directions at once, a structure with quaquaversal dips about an axis which may have any attitude. Such a structure is either a dome or a basin if the axis is vertical. In places where the axis is horizontal, it is doubtful if this type of structure could ordinarily be recognized as such; it is a dome or basin on edge. However, in areas of deep-zone deformation, domes and basins, large and small, are fairly easily recognized, and others of which only an edge is exposed are probably much more common than usually suspected.

The writers have observed the wonderfully exposed and intensely metamorphosed rocks in the regions north and east of Georgian Bay which exhibit the characteristics of deep-zone metamorphism. It is the purpose of this paper to describe some local structures found in this region which seem to furnish a key to the interpretation of the regional structures.

Outcrops on Lookout Island show a general parallelism of rock layers, indicating stratification of beds with different original compositions. Proceeding from this premise of original parallelism of the

layers, the writers conclude that the nature and mechanics of deformation can be interpreted from the outcrop pattern.

By the term "deep zone" the writers imply a depth at which rocks fail in the manner more like that of hydrostatic than of rigid members. This implies a depth at which it is impossible for cavities to exist for any length of time and equally impossible for the transmission of continuous vectorial stress. It implies also a relative incompetency of all rocks in this zone and their potentially plastic or mobile behavior under stress. The term is an expression of physical condition rather than position.

Using the term "plastic flowage" of rocks in this paper, the writers refer to a more or less homogeneous yielding of a given rock to stresses without failure by rupture and without change in volume. The actuality of plasticity or quasi-plasticity in rocks subject to certain physicochemical conditions has been well established by field evidence and confirmed by laboratory experiments and petrofabric analyses, although the exact mechanics of this movement is as yet not definitely established. An analysis and summary of the literature pertaining to plastic flow has been presented by Knopf.[1]

FIELD WORK

Field studies of rocks of the deep zone have been followed by the senior author north and northeast of Georgian Bay during many field seasons in the service of the Geological Survey of Canada and by the junior author in the general area east of the Muskoka lakes during the seasons of 1938 and 1939.

AREA OF DETAILED MAPPING

Certain characteristic deep-zone structures have been mapped in detail by the senior author on Lookout Island, Point au Baril, Ontario. This island is on the northeast shore of Georgian Bay, 15 miles south of Byng Inlet at 45° 32′ 30″ N. Lat., 80° 30′ 30″ W. Long. It presents a rock pavement swept clear of all cover as a result of glacial and wave erosion, so that it permits mapping in great detail.

[1] E. B. Knopf and E. Ingerson, "Structural Petrology," *Geol. Soc. Amer. Mem. 6* (1938). Reference must also be made to two works published simultaneously since this paper was written: David Grigg, "Experimental Flow of Rocks under Conditions Favoring Recrystallization," and R. W. Goranson, "Flow in Stressed Solids: An Interpretation," *Bull. Geol. Soc. Amer.*, Vol. LI (July 1, 1940).

Two well-exposed areas 100 feet by 60 feet and 60 feet by 60 feet, exhibiting characteristic structures, were surveyed into sections 10 feet square, and each section was mapped as a unit. Later these units were compiled into single maps as shown in Figures 1 and 2. The maps have been indexed with co-ordinate references for use in the text.

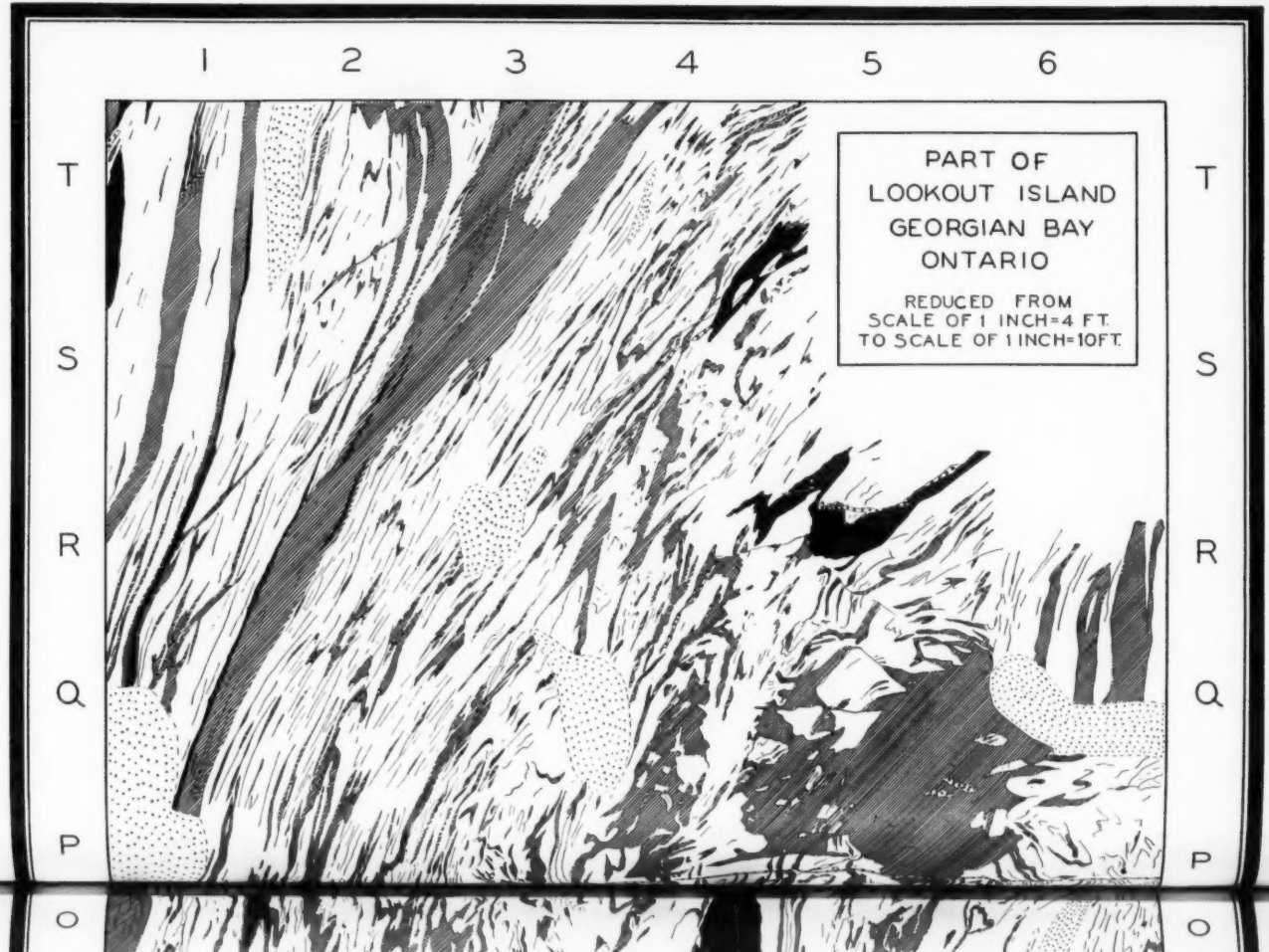
ROCK TYPES

The rocks exposed in this area are, for the most part, pale-gray granitic gneiss interbedded with pink gneiss and layers of dark chloritic schist. Both the contrasting colors of the rock layers and the definite gneissic banding greatly aided in detailed mapping. The gneisses vary considerably in texture. The gray gneiss varies in texture from medium to coarse grain, and the pink varies from fine to coarse, but the chloritic schist remains fairly constantly medium-grained. In composition the gray gneiss varies from granitic to granodioritic, but the pink gneiss is persistently alaskitic. The dark mineral in the gray gneiss is prevailingly biotite, although in some areas hornblende and magnetite appear. These gneisses are penetrated both parallel and transversely to the bedding by giant granite and minor quartz veins and are paralleled by rare, fine-grained, olivine diabase dikes. The contacts between the layers are definite but not planar; crystals of both rocks interlock across the contact, showing no solution or reaction.

GEOLOGICAL RELATIONS OF ROCK UNITS

The exact time-relationship of the various bands shown in the exposure is somewhat uncertain. Relationship to the fault structures and their relatively unmetamorphosed condition show that the quartz and giant granite veins were formed after the major metamorphism. They are offset by small faults but are not much metamorphosed.

The greatest problem is presented in the relationship of the chloritic schist and the gray and pink gneisses. All three of these probably existed prior to the major metamorphism. (The pink gneiss following the fault zone at *A-2* appears to be postmetamorphism but may be explained as drag along the fault or by other causes to be discussed later.) The pink gneiss in many places has an invasive atti-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SCALE OF 1 INCH=4 FT.
TO SCALE OF 1 INCH=10FT.

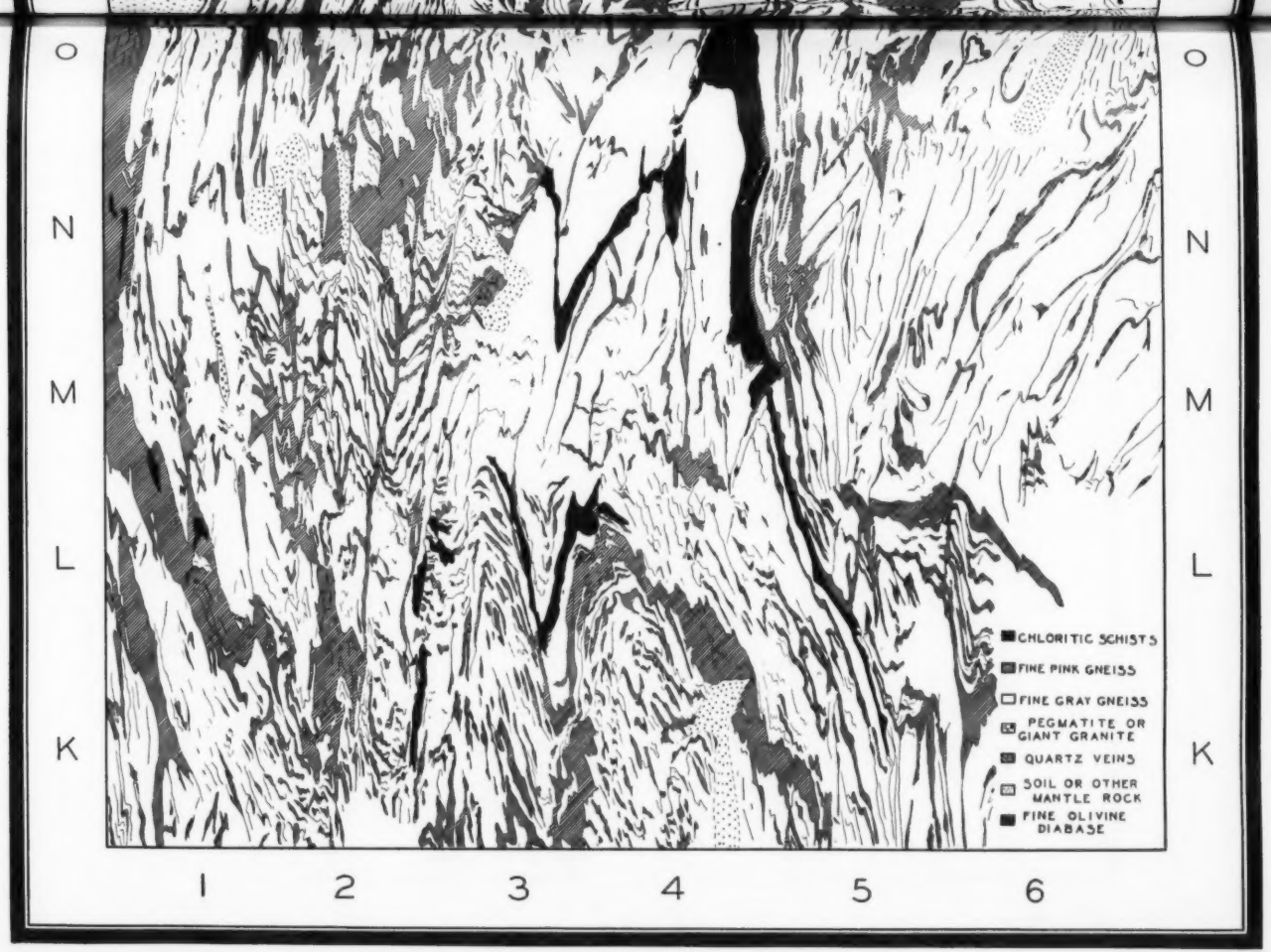

FIG. 1.—Part of Lookout Island, Georgian Bay, Point au Baril, Ontario

FIG. 2.—Lookout Island, a short distance from the area shown in Fig. 1

tude, cutting across the other two layers, thus forming a trellis-like structure (*M-2, L-6*) which resembles lit-par-lit injection of pink aplite into the gray gneiss and chloritic schist complex. This interpretation is made questionable, however, because the gray gneiss in several places apparently invades the pink gneiss and the chloritic schist (*M-0, A-3*) and because the gray gneiss in turn is apparently invaded by the schist ($C\text{-}2\frac{1}{2}$). In the more highly deformed areas practically all conditions of mutual invasion exist. However, in the less disturbed areas these rock types assume a parallelism of characteristically sedimentary appearance.

Three possible explanations for the relationship of the rock facies are worthy of consideration: (1) lit-par-lit injection or magmatic intrusion of pink aplite into the gneissic complex; (2) complete or selective *anatexis* of the rock; and (3) mutual *plastic invasion* of the rock layers by solid flow.

Lit-par-lit injection is suggested by the trellis-like structures developed by the pink gneiss in the gneissic series (*M-2, L-6, M-1, S-2, O-4*) and by the occasional cross-cutting attitude of the pink gneiss across the gray gneiss and the chloritic schist. However, in order to account for the complexly drag-folded and sheared structures developed in the pink gneiss, it would have been necessary for the injection to have occurred either prior to the major deformation or contemporaneous with it. It would then be impossible to explain the lack of comparable deformation of any one of the discordant pink "dikes" penetrating deformed areas which contain the same pink material in a sheared and drag-folded condition (*L-2*). Likewise, such as explanation as lit-par-lit injection would explain only the cross-cutting attitude of the pink aplite and could not account for the invasive relationships of the other facies into the aplite or the well-preserved, drag-folded lenses of gray gneiss enclosed in the pink gneiss (*A-6*).

The idea of "Vane sheets,"[2] intrusive sheets parallel to the linear structure of the country rock, encounters the same difficulties as lit-par-lit magmatic injection. It cannot explain the mutually invasive relations of all the beds, and it cannot explain why the sheets

[2] R. S. Cannon, "Geology of the Piseco Lake Quadrangle, N.Y.," *New York State Museum Bull. 312* (1937), p. 58.

which cut across the structure should be so little deformed as compared with those parallel to the bedrock structures.

J. J. Sederholm[3] has explained phenomena of this general type as "palingenesis." He says: "Palingenesis refers to the geological age, meaning that the rock has been reborn, in other words received a new eruptivity." If palingenesis in this case could have involved *complete anatexis*, or melting of the rocks, one might expect the bands to lose their individuality or at least to show gradation between one band and its neighbors. The contacts, however, are relatively sharp, showing no solution or reaction. The coarse and variable texture of the gneiss would be difficult to explain if the rock had been actually remelted. If the rock had been liquefied as a result of heat generated during deformation, it would offer now a stony rather than a coarse texture.

Selective anatexis as an explanation of the invasive structures is even less satisfactory than complete anatexis. In order to explain the sharp contacts and mutual invasions, one must postulate the liquefaction of each layer in turn with alternating periods of solidification. This would involve serious thermodynamical contradictions. Whereas dynamic fluctuations may occur relatively rapidly in the deep zones, thermal fluctuations are relatively slow and are resisted by mineralogical changes according to Van't Hoff's reaction isochore.[4]

The tendency for the major volume of the thin beds to be concentrated into the apexes of the folds is one of the most pronounced features shown by the mapping. It also appears that the identically same pink gneiss which gathers into the "hooks" and Y's of the minor folds was free to migrate along zones of incipient slip or shear, forming trellis-like structures, invasive nodes, and "dike" transgres-

[3] "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland. Part II," *Bull. Comm. Geol. Finland*, No. 77, Part II (1926), p. 135.

[4] At constant volume a rise of temperature produces a displacement of equilibrium toward the absorption of heat, i.e., those minerals will form that develop with an absorption of heat as shown by the relation

$$\frac{d \ln Kc}{dT} = \frac{E_v}{RT}.$$

E = heat absorbed at constant volume
Kc = equilibrium constant at constant volume
R = molar gas constant
T = absolute temperature

sions. In several places the dark schist was broken by sharp folding and stretching; meanwhile, solid continuity was maintained by the apparent solid flow of the gray gneiss which now occupies the space between the broken pieces of schist (*N-4, L-3*). Likewise at *P, Q-4, 5*, the spaces between the fragments of brecciated gray gneiss have been filled by solid flow of the pink gneiss. By postulating a high degree of plastic mobility of the rocks in the deep zone, one may explain the structural relationships found on Lookout Island by *mutual invasion* of the rock facies. Fracture and shear planes developed in the later stages of the rock deformation probably served as zones of reduced pressure, which were quickly usurped by inflow of the adjacent rock material. The most mobile of the rock facies would naturally occur most frequently as the fracture filling, and it is apparent from the maps that the pink gneiss was the most mobile of the rock facies in these outcrops, since it forms most of the crisscrossing structures. The energy transformations accompanying such plastic flow are relatively small, because the changes both in volume and in latent heat of fusion are negligible.

FAULTS

In spite of the highly deformed and sheared nature of these deep-zone rocks, faulting contemporaneous with the major period of deformation is not much in evidence. Minor faults do occur, indicating that a certain degree of rigidity existed at least temporarily during deformation, but in general the shear forces seem to have been satisfied by stretching or shortening of the layers rather than by rupture.

Fault structures on Lookout Island are generally of a high-angle type, either dipping steeply toward the downthrow side or dipping vertically. They are characterized by unusual conditions of drag in which the beds are drawn out along the fault for a considerable distance in the direction of movement (*B-C*). The amount of displacement in some of the faults varies as traced along the strike (*O-O*) and appears to reverse direction,[5] resulting in a pinching or spreading of the beds where they are cut by the fault. For instance, in the fault at *O-O* the north side has moved relatively west at *O-*$\frac{1}{2}$, *O-*$2\frac{1}{2}$, *O-*$4\frac{1}{2}$,

[5] This may be apparent rather than real, depending upon the true direction of displacement along this fault line, which probably was not parallel to the strike of the fault trace on the outcrop.

but it appears to show no shift at *O-2* and *O-4¼*. An eastward displacement appears at *O-1½* and *O-5*.

The major faults in the outcrops trend in an east-west direction, cutting at nearly right angles to the trend of the folded structures. These faults are generally occupied by giant granite veins and were probably formed during a period of faulting after the major deformation, since they cut across the folded structures. Small shear planes, probably formed during the later stages of the major deformation, are developed parallel to the trend of the folded structures in a north-south direction. These are commonly occupied by the pink gneiss member of the complex. A few minor displacements run oblique to the major trends. These, too, were probably developed during the late stages of the major deformation and are occupied by the pink gneiss.

SCHISTOSITY AND FLOW LINES

Throughout the area of study schistosity is parallel to the bedding. This condition persists throughout the pre-Cambrian Shield nearly everywhere, as reported by many writers.[6] This is a point of great importance for the interpretation of the structures of the area, because, were the facts otherwise, or were there even a reasonable doubt as to the point, the question would arise as to how much of the apparent structure was due to shearing and how much to actual bedding.

It is well known to geologists that slaty cleavage in a region of intense folding runs transverse to the bedding in many places. In closely folded schists it runs nearly parallel to the axial planes, but there is obviously no slaty cleavage in rocks so severely metamorphosed that they are gneisses.

Direction of movement in the plane of schistosity is indicated by the elongation of nearly equidimensional minerals such as feldspar

[6] A. C. Lawson, "The Archean Geology of Rainy Lake Re-studied," *Geol. Surv. Canada Mem. 40* (1913), pp. 1, 14, 75; C. H. Stockwell, "Reindeer Lake Area, Saskatchewan and Manitoba," *Geol. Surv. Canada Summ. Rept. B* (1928), p. 67*B;* J. F. Wright, "Kississing Lake Area, Manitoba," *Geol. Surv. Canada Summ. Rept. B* (1928), p. 82*B;* and "Geology and Mineral Deposits of a Part of Northwest Manitoba," *Geol. Surv. Canada Summ. Rept. C* (1930), p. 13*C;* and A. F. Buddington, "Granite Phacoliths and Their Contact Zones in the Northwest Adirondacks," *New York State Mus. Bull. 281* (1929), pp. 53, 82.

porphyroblasts into lens-, cigar-, or pencil-shapes, or by orientation of minerals with elongate habit into parallel arrangement. On Lookout Island flow lines generally lie in vertical planes, striking between N 20° W. and north. The direction of the linear structure varies little in strike but considerably in plunge and is not parallel to the dip of the foliation, bedding, or schistosity of the rock.

AGMATITIC BRECCIAS

Agmatitic breccias are seen (*A, B, C-4; N-4*) where the dark chloritic-schist layers have been pulled apart and the surrounding gray or pink gneiss has invaded the spaces between the broken pieces. The dark chloritic material is usually squeezed or pulled into sharp-pointed ends enclosed in the surrounding gneiss which fills both the wide spaces and the narrow cracks between the separated pieces of dark rock. On the crests of domal structures these breccias may be viewed in a horizontal plane (*P, Q-5, 6; P-4; N-2*). The gray gneiss has been shattered into many angular fragments cemented by the pink feldspathic gneiss. There is no relation between the composition of the brecciated mass and the cementing material, and the contacts between them are relatively sharp. Some of the brecciated pieces show an exaggerated sharpness of the corners as if the pieces had been drawn out into points of squeezing. This pointing could not have been produced by rupturing or shattering forces but only by hydrostatic squeezing of the fragments. The pink gneiss now filling the spaces between the fragments must occupy the space of the medium through which such pressures were transmitted.

During the folding of the interbedded pink and gray gneisses, the pink gneiss gathered into the apexes of the folds. The flow of the pink gneiss into the apexes occurred more rapidly than the less mobile gray gneiss or chloritic schist could adjust to the movement. As a necessary consequence of the mutual adjustment of a less plastic medium to one more mobile, fractures developed in the less mobile medium (gray gneiss). These fractures were forcefully invaded by the pink gneiss, which wrested apart the fragments of gray gneiss. This does not imply that the gray gneiss lacked plasticity; rather it indicates that it possessed a lower order of plasticity than the pink gneiss.

Sederholm[7] described evidence of fusion in somewhat similar rock mixtures in Finland, which he called "agmatites"; however, the writers believe that the examples in this area are better explained by rock flowage without anatexis.

DRAG FOLDING

An intricate pattern of drag folding is developed in the outcrops as a result of the differential movement of the layers. Various stages

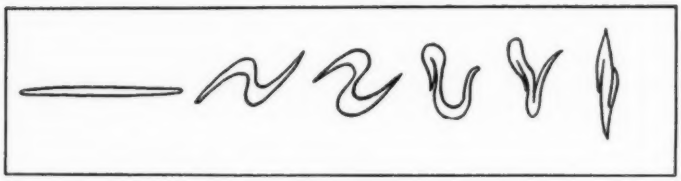

FIG. 3.—Diagram showing the stages of deformation of the drag folds in the Lookout Island map area.

in the development of these distorted folds, as found in the outcrop, are shown diagrammatically in Figure 3. In the advanced stages the S folds may take the shape of "hooks" and Y's and may in later stages be completely destroyed, leaving merely a lens or stringer.

DICTYONITIC STRUCTURES

The term "dictyonitic" is used in this paper to designate the net-, spider-, or trellis-like streaks frequently developed in deep-zone rocks, resulting from the introduction or flow of rock material into joint, fracture-cleavage, or shear planes and along bedding or schistosity planes. Excellent examples of this type of structure from neighboring localities in the Georgian Bay region have been described as spiders by Quirke,[8] and others are shown in the map area at *M-2*, *L-5*, *P-4*, *S-2*, where the pink alaskite forms all the criss-crossing layers. This material is identical with the pink gneiss in the bedded layers.

There are two distinct directions of transgression; one a northeast-

[7] *Op. cit.*, pp. 16–20.

[8] "Streaks in the Deep Zone Gneisses," *Trans. Roy. Soc. Can. Sec. IV*, Vol. XXV (3d ser., 1931), p. 253, Pl. VII.

southwest direction apparently following fracture-cleavage planes (*S-2, N-5, P-4, R-1, M-3*), the other direction parallel to the north-south trend of the folds following shear planes (*L, M, N-2; L-5½; L, M, N-1½*). An idealized diagrammatic sketch of dictyonitic structures developed along planes of fracture cleavage is shown in Figure 4.

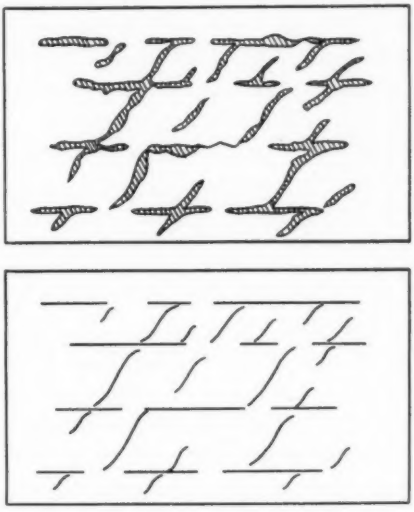

FIG. 4.—Diagram of dictyonitic streaks in a well-bedded gneiss. *Lower*, Diagram of fracture cleavage in a well-bedded series of sedimentary rocks which displays the same general form as the dictyonitic gneiss.

The exact origin of this type of structure is probably varied and different in different localities. Three possibilities of origin present themselves: (1) introduction by magmatic solutions; (2) lateral segregation;[9] and (3) injection of material by rock flow into zones of weakness or of slightly reduced pressure. For reasons previously discussed the writers prefer the last explanation in this particular outcrop. Lateral segregation may be a cause for these structures in other localities and a contributing factor in this area; however, it tends to develop a pegmatitic texture. In the cases here considered there is no textural difference between the transgressive and bedded alaskite; both have a granulitic texture.

FORMATIONAL CONTACT PHENOMENA

In certain places interbedded rocks develop mutually invading structures as a result of intense deformation under favorable condi-

[9] A. C. Lane, "Origin of Granites as Well as Metacrystals by Selective Solution—a Recantation," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), p. 704.

tions. Such features in marbles and associated gneisses are common everywhere and are geologically commonplace. Cases of mutual flow of feldspathic gneisses are somewhat more unusual. The chloritic schist commonly invades the boundaries of the gray gneiss with sharp-edged or lenticular shapes. This feature is well displayed at *R-5*. P. J. Holmquist[10] has pointed out the relationship of the drawing-out of the weaker material into oversharpened points and the development of broad convex faces on the side of the more competent masses. The contacts between the gray and pink gneisses vary considerably in their relationships. Most commonly the pink gneiss develops sharp-pointed border invasions into the gray gneiss, while the gray gneiss invades the pink with broadly convex nodes. Sometimes the situation may be reversed and the gray gneiss will develop sharp-edged invasions, or else the gneisses may develop equally pointed or convex contact borders.

GIANT GRANITES (PEGMATITES)

Must we consider the giant granite of the locality as a fine-grained pegmatite, and, if so, must it be an intrusive igneous rock? K. K. Landes defines a pegmatite as

> an intrusive holocrystalline rock composed essentially of rock-forming minerals which are developed, in part, in individuals larger than the grains of the same mineral occurring in the normal plutonic equivalent.[11]

It seems significant that the composition of the giant granite differs little from that of the surrounding gneisses; there are no distinctly hydrothermal or contact-metamorphic minerals such as tourmaline, etc., present in the giant granite veins; giant granite facies are developed locally in the gneisses, grading into the finer-textured material; and some of the giant granites appear to occupy isolated faults and pockets without apparent feeders. Generally only two dimensions could be observed, so that this last observation cannot be conclusive. However, Sederholm[12] described "pegmatites" from

[10] "The Relative Plasticity of Rock Masses under the Influence of Dynamic Deformation," *Fennia 50*, No. 33 (Helsingfors, 1928), p. 8; Quirke, "Differential Flow of Silicate Rocks," *op. cit.*, p. 265, Pl. II, *A*, *B*, *C*.

[11] "Origin and Classification of Pegmatites," *Amer. Min.*, Vol. XVIII (1933), p. 34.

[12] *Op. cit.*, No. 58 (1923), p. 104.

Finland in isolated cavities in metabasalt, the filling of which he ascribed to materials leached out of such portions of the basic rocks as became broken up during granitization. Lane[13] has postulated lateral segregation as an origin for the Maine pegmatites. A segregation granite from near Georgian Bay which was generated in place along a zone of fracturing has been sketched and described by F. F. Grout.[14] These examples show marked resemblances to many of the giant granite veins of Lookout Island. These latter probably were also formed in place without feeders from igneous injection.

The giant granite veins in these outcrops may be considered as of several types:

1. Conspicuous veins following fault zones (*P-P, O-O, B-C*, etc.)
2. Veins developed parallel to the schistosity (*O-6, B-6, A-2, R-4*, etc.)
3. Veins apparently following planes of fracture cleavage (*R-5*)
4. Apparently isolated pockets of giant granite (*P-5, C-2½*)

The fractures or openings developed in the rocks in the late stages of deformation probably served as channels for molecular interchange and migration or as zones of reduced pressure that might be invaded bodily by the more plastic rock materials. Mylonites formed along the fault might have formed a nucleus for recrystallization and the formation of a "blasto-mylonite" within a hydrothermal medium of exchange. Probably all three of these processes contributed to the formation of the pegmatites shown in these outcrops.

FOLDS

The outcrops on Lookout Island present a complexly folded series of gray and pink gneisses and chloritic-schist layers with dips varying from 0° to about 90°. The folds trend generally north-south and are characterized by marked thickening in both crests and troughs of the folds and irregular pinching on the flanks. The major folds of the area plunge steeply to the north or to the south in a north-south plane, in places varying from nearly vertical to horizontal in domal structures (*P, Q-5, 6; P-4; N-2; A-2*). This flattening is indicated on the map (Fig. 1) by the widening of the outcrop pattern.

[13] *Op. cit.*, p. 704.

[14] *Petrography and Petrology* (New York: McGraw-Hill Book Co., 1932), p. 189.

The composite structure shown in Figure 1 is a doubly plunging syncline or saddle fold plunging to the north and to the south and is flattened across the central portion by a cross-fold trending generally northeast-southwest. This structure is shown diagrammatically in Figure 5. The pink alaskite forming the domal structures is identical in texture and composition with that which occupies the hooks and Y's of the minor drag folds. A similar type of saddle fold is shown in Figure 2 at *A-2*, where the cross-fold apparently does not persist far into the adjoining rocks but dies out in a distance of 5–8 feet. This type of folding is probably one of the characteristic features found in rocks which have been deformed in the deep zone.

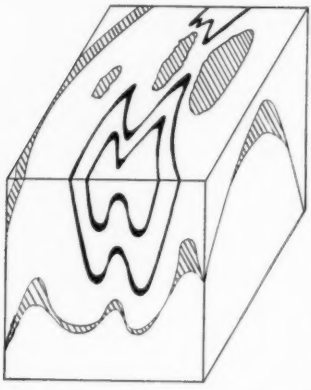

FIG. 5.—Idealized diagram showing the saddle fold mapped in Fig. 1.

DOME AND BASIN VARIETY OF FOLDING

The folding along the two axes does not necessarily indicate two periods of folding. The writers believe that the folding occurred along both axes simultaneously in response to multiple-force components. Such folding would not be possible at shallower depths, where most rocks possess a high degree of rigidity; in such a case the folded beds are weakened in a direction normal to the axial plane and greatly strengthened in a direction parallel to it. All force components striking oblique to the axial plane ordinarily are resolved along the direction of weakness, normal to the axial plane of the initial folding, and no cross-folds develop. However, in the deep zone the rocks possess less rigidity and tend to behave in the manner of highly incompetent layers. Forces are transmitted through them in any definite direction for only limited distances, and stresses are accommodated by rock flowage. Under conditions such as described there would be less resolution of force components, and folding along two or more axes could occur simultaneously or at different

periods. As a result of this mobile, incompetent condition of the rocks, in the general case dome and basin structures characteristically tend to develop in the deep zone rather than the familiar anticline and syncline structures of shallower zones.

APPLICATIONS TO REGIONAL STRUCTURES

Is it possible to apply local structures such as found on Lookout Island to the regional structures of the Canadian Shield? Sederholm and his associates have succeeded in extending observations on a small scale to apparently similar phenomena on a large scale in Finland and Scandinavia. Following the example set by these men, the writers believe that the nature of the structures as determined on Lookout Island may furnish a key by which the complex structures, as mapped by F. D. Adams and A. E. Barlow, and others, from this general region may be correctly interpreted.

Adams and Barlow[15] have mapped a chain of "batholiths" intruded into a complex series of paragneisses and marbles in the Haliburton-Bancroft areas. A copy of a portion of their map is shown in Figure 6. There are several features present in these plutonic intrusions that are extremely unusual for "batholithic" intrusions:

1. The intrusions are all closely bordered by the same formation of paragneiss.
2. The "batholiths" are everywhere concordant to the structure and foliation of the country rocks.
3. The foliation and banding of the "batholiths" parallels the sedimentary structures.
4. The "batholiths" occur only on the concave sides of the outcrop pattern of the folded paragneisses, indicating a close relationship to the folded structures.
5. The joint patterns of the "batholiths" do not seem to resemble the joints related to flow structure of intrusive plutonics but follow a regional pattern.
6. Pegmatites are largely discordant and follow a regional direction throughout the area. Their trend does not seem to be influenced

[15] "Geology of the Haliburton and Bancroft Areas, Ontario," *Geol. Surv. Canada Mem. 6* (1910).

by rock boundaries or structures, and their orientation and distribution throughout the area bear little relation to the "batholithic" intrusions.

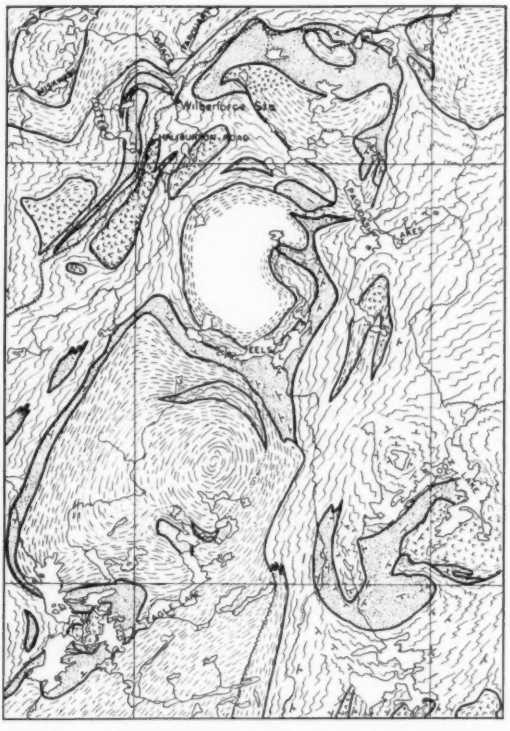

FIG. 6.—Map, after Adams and Barlow, showing Burleigh, Anstruther, Monmouth, and Deer Lake batholiths.

These observations have been made by the writers in the Haliburton-Bancroft and adjoining areas and have been partly anticipated by Ernst Cloos.[16]

Cloos suggests the possibility that the Loon Lake pluton (in the

[16] "The Loon Lake Pluton, Bancroft Area, Ontario, Canada," *Jour. Geol.*, Vol. XLII (1935), pp. 393–99.

lower right portion of the map), having a funnel or basin structure, may be a sill intruded between the sedimentary layers. This explanation is readily applicable to the other "batholithic" structures of the area. Domal and basin structures are not confined to the areas of exposed granite gneiss, and it is apparent from a study of Figure 6 and a further study of Adams and Barlow's map that these structures occur just as frequently in the sediments as in the supposedly igneous intrusions. The implication naturally follows that these domal and basin structures do not represent batholithic intrusions but are either large sills intruded between the sedimentary layers or highly metamorphosed members of the sedimentary series. In either case, they are concordant with the bedding and are folded structures rather than plutonic structures. The writers wish to suggest cross- or quaquaversal folding similar to that described from Lookout Island as a possible origin of these domal structures. An idealized diagram showing the application of this interpretation to these structures is shown in Figure 7.

The implication of the structures in relation to the areas of apparently massive rock leads to the conclusion that the massive areas are, in general, merely flat-lying parts of the interbedded gneisses and that the areas of well-defined structure represent those places where the layers are standing at high angles. If it were possible to view a vertical plane through a solid block of this terrane, the structural appearance of well-bedded areas and massive areas would be the reverse of the exposures of the same rocks on the horizontal surface.

Following this point of view the whole terrane is not a typical illustration of an area affected by batholithic invasion. It exhibits excellently the dome and basin type of folded structures produced by plastic rock flow in the very deep zone.

This conclusion is well supported by the mapping and observations of the senior author in the Muskoka-Parry Sound areas, where the occurrence of domal and basin structures in banded gneisses is definitely outlined by a thin bed of marble. Near Parry Sound well-bedded, steeply dipping paragneisses show a bewildering series of dip-and-strike changes. When the possibility of an edgewise section through dome and basin structures is realized, then the changing dip

and strike of the paragneisses takes a definite meaning. It is apparent that the axes of these structures are nearly as commonly horizontal as vertical, offering an entirely different aspect at the surface of erosion. The apical portions of the domes and basins often have horizontal foliation, giving them the massive appearance of plutonic

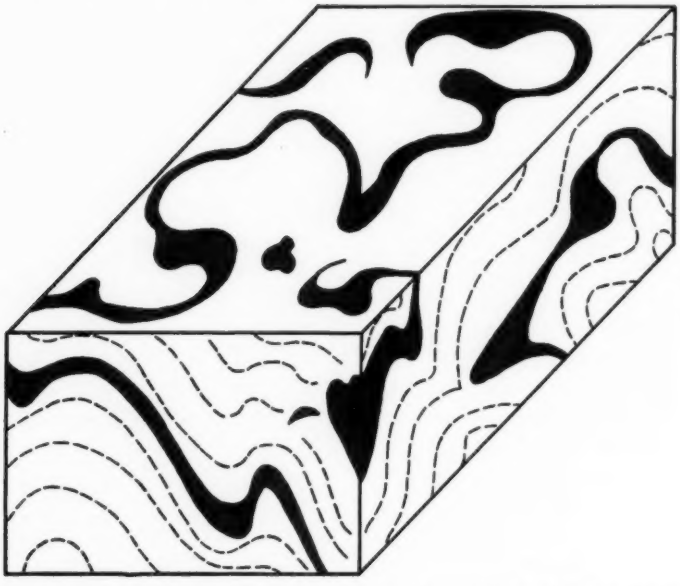

FIG. 7.—An idealized sketch showing the writers' interpretation of certain "batholithic" structures of the Haliburton-Bancroft areas.

intrusions. Yet the interbedding of the thin limestone bed with these identical gneisses gives proof of at least part sedimentary origin. The relation of jointing, schistosity, and the arrangement and distribution of pegmatites to the domal and basin structures seems to be very similar to those in the Haliburton-Bancroft areas and to those shown in the detailed maps here described.

CONCLUSION

Under the physicochemical conditions of the deep zone many discordant structures result from solid flow and mutual invasion of

rock members in a highly plastic or quasi-plastic condition. These structures may be distinct from magmatic or hydrothermal injections and involve no anatexis.

Dome and basin folding in place of simple anticline and syncline folding is the most diagnostic and characteristic structure of the deep zone. Folding occurs along two or more axes simultaneously. The axes vary greatly in both their relationships to one another and their relationships to the surface, and until this fact is recognized, many regional structures of the deep zone present only a confusing series of dip-and-strike changes. Where the axis of a dome or basin is vertical, bedding and schistosity, of course, are horizontal; consequently many outcrops which have been interpreted as parts of the roofing of plutonic intrusions probably belong to deep-zone domal structures.

ACKNOWLEDGMENTS.—Grateful acknowledgment is made to the Geological Survey of Canada and to the senior author's field associates of the seasons 1923–31, especially Mr. William Gerrie (1924–25), Dr. Reginald Pegrum (1925–27), Dr. Harold Fairbairn (1928), Dr. W. A. Jones (1929), Drs. Frank Foley and Bruce Freeman, and Messrs. E. L. MacVeagh and William Wright (1931).

PERSISTENCE OF HEAVY MINERALS AND GEOLOGIC AGE

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ABSTRACT

The apparent increase in complexity of the heavy-mineral suites of arenaceous sediments with decrease in age of the deposit is confirmed by compilation from published records. Such increase in number of mineral species in the younger deposits is due to (*a*) greater complexity of terrane from which the younger sediments were derived or (*b*) disappearance by solution of the less stable species in the older deposits. The latter alternative is shown to be the correct explanation, since the order of persistence of the common rock-making heavy minerals worked out from the tabulation is identical with Goldich's "stability series," which is the order of survival of minerals subject to weathering. The stability series is expanded to twenty-five common constituents of sediments.

INTRODUCTION

Students of heavy minerals have long noted an apparent increase in complexity of heavy-mineral suites with decreasing geologic age. J. Thoulet,[1] for example, was one of the first to make this observation. P. G. H. Boswell,[2] who later reaffirmed Thoulet's generalization, attributed the increased complexity to (1) greater complexity of terrane from which the younger sediments were derived and (2) disappearance by solution of the less stable species. More exact information on persistence of the common heavy minerals in the stratigraphic column is needed before the causes of progressive differences with decreasing geologic age can be ascertained.

The presence of a particular mineral in a sediment requires the presence of that mineral in the parent-rock, its ability to survive weathering of the parent-rock and to resist abrasion and decomposition during transportation of the sediment, its deposition with the sediment (and not its removal by sorting action), and its ability to survive post-depositional solution or decomposition. R. Dana Russell[3] has shown that loss during transportation is not an impor-

[1] "Notes de lithologie sous-marine," *Ann. Inst. océanog.*, Vol. V, Fasc. 9 (1913).

[2] "Some Aspects of the Petrology of Sedimentary Rocks," *Proc. Liverpool Geol. Soc.*, Vol. XIII (1923), pp. 231–303.

[3] "Mineral Composition of Mississippi River Sands," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 1307–48.

tant factor in the Mississippi River. Most minerals, even the amphiboles and pyroxenes, withstand abrasion well. The general absence of these and other minerals from the older sediments cannot, therefore, be ascribed to their inability to survive transportation. Neither can their absence be attributed to the lack of these minerals in the parent-rock, since they are present in the source rocks of all ages. Since they occur in the younger geologic deposits, it may be assumed that they were also deposited in the ancient sediments. Russell was therefore driven to the conclusion that they disappeared following deposition by intrastratal solution. The purpose of this paper is to investigate intrastratal solution, to estimate the survival or persistence of the more common heavy minerals in sediments, and to measure the increase in complexity of heavy-mineral suites with decrease in geologic age.

TABULATION OF DATA

METHOD OF TABULATION

The data were collected from published papers. Sedimentary petrologists report their findings by listing the minerals observed, by estimating the relative abundance of the several species and giving a verbal description of their abundance, and by counting the grains of a representative sample and calculating the relative frequencies. It is apparent that uniformly reliable information on the abundance of a particular species in the sediments of the various periods is difficult to obtain from the existing literature. The writer, therefore, postulated a relationship between the abundance of a given mineral species and the number of times such species is reported in heavy-mineral studies. A mineral reported in 90 per cent of the formations or areas examined for a given period is probably more abundant than the same mineral reported in but 5 per cent of the published records of another geologic period. Accordingly, the author tabulated the reported occurrences of the more common heavy minerals for each formation or region on which published data were available. From this tabulation it is possible to compute the frequency of occurrence, in percentages, for each species for any desired period. Table 1 summarizes the frequency of occurrence for the more common mineral species.

This method no doubt emphasizes the rarer constituents. A mineral of less abundance, though persistent, receives just as high a frequency-of-occurrence number as a much more abundant but

TABLE 1

FREQUENCY OF OCCURRENCE
(In Percentages)

No.	Mineral	Pre-Keweenawan	Keweenawan	Early Paleozoic	Late Paleozoic	Mesozoic	Tertiary	Pleistocene	Recent
1.....	actinolite	0	8	3	4	3	7	8	26
2.....	anatase	50	62	50	65	50	36	28	20
3.....	andalusite	10	0	0	2	26	49	28	45
4.....	apatite	100	85	23	45	47	11	59	53
5.....	augite	10	0	12	14	18	16	62	67
6.....	biotite	40	38	29	37	66	40	59	57
7.....	diopside	0	0	3	2	13	3	23	43
8.....	epidote	70	54	12	24	58	61	95	92
9.....	garnet	70	62	79	76	95	73	92	95
10.....	hornblende	70	62	32	12	50	54	90	92
11.....	hypersthene	0	0	15	12	18	13	36	58
12.....	ilmenite	100	100	21	57	66	79	77	83
13.....	kyanite	10	0	6	8	58	63	77	70
14.....	magnetite	100	15	38	51	71	53	95	85
15.....	monazite	0	0	3	29	18	24	41	25
16.....	muscovite	20	0	21	63	55	61	38	38
17.....	olivine	0	0	0	0	0	0	13	18
18.....	rutile	50	85	68	96	84	85	77	75
19.....	sillimanite	0	0	0	0	13	30	23	37
20.....	sphene	50	15	6	10	26	33	59	58
21.....	staurolite	10	15	18	43	66	71	69	77
22.....	topaz	0	0	9	0	16	21	26	28
23.....	tourmaline	70	77	100	98	89	94	80	93
24.....	zircon	100	100	100	100	92	93	95	95
25.....	zoisite and clinozoisite	0	8	0	4	24	20	36	42
26.....	feldspar	.....	.....	21	43	32	46	46	53
Total occurrences ...		10	13	34	51	38	70	39	60

equally persistent mineral. Zircon and hornblende, for example, occur with about equal frequency in the Recent sediments, though hornblende is very much more abundant, as a rule, than zircon in these deposits. The frequency of occurrence, therefore, is not

strictly a measure of abundance when two different minerals are compared one with the other. When the frequency of occurrence of a particular mineral in one time period is compared to the frequency of occurrence of the same species in another time period, the two values recorded are believed to bear a direct relation to the relative abundance of that mineral in the sediments of the two periods in question.

RELIABILITY OF DATA

A number of difficulties in tabulation were encountered. Certain species were reported so infrequently, even from Recent deposits, that no adequate or statistically valid conclusions could be drawn. The study was therefore confined to the more common minerals. Data on certain minerals are subject to special error. The micas, for example, are reported by some writers as "light" minerals, by others as "heavy" minerals, and by others omitted altogether. In the latter case it is difficult to know whether the light minerals were simply ignored (as is often the case) and the mica therefore overlooked or whether the mica was truly absent.

Another difficulty resulted from grouping of certain minerals under such designations as "opaques," "black opaques," "iron ores," etc. Since magnetite and ilmenite are probably both present, the frequency of opaques was added to the frequency of each of these two minerals. This correction affected primarily the data from the Tertiary, Pleistocene, Recent, and pre-Cambrian. Excepting for the pre-Cambrian, the trend of the data for these two species is fairly uniform, and the correction seems to be justified. Other species were also occasionally grouped under such headings as "carbonates," "micas," "amphiboles," etc. Data on still other minerals are rendered uncertain by the method of treatment of the sample. An acid digest is commonly used to dissolve carbonate cements or remove iron oxide coatings on the grains. Such treatment makes the frequency of occurrence of the acid-soluble species, notably apatite, open to doubt.

Also apparent are differences in thoroughness of investigation. Some workers report exceptionally complete lists of minerals, while others report only the principal species and pass over the minor constituents. The length of the list reported is partly dependent

upon the number of samples examined. Extending the latter increases the chances of finding a grain or two of the rarer species. Fortunately, these difficulties—as well as most of the others—are not progressive in time and would not, therefore, affect the trends observed.

Some trouble arises also from certain species which are in part authigenic. Many writers made no distinction between authigenic and allogenic minerals. In other cases the issue was in doubt. This difficulty applies mainly to the titanium minerals, especially anatase and rutile. No attempt was made in this tabulation to differentiate between the two.

Finally, the question of whether the tabulation is adequately representative of all sediments or not may be raised. Are the reported occurrences well enough distributed geographically and stratigraphically? And do they adequately represent all environments of sedimentation? Since the studies cover mainly European—notably British—and American localities, it is believed that the complex geology of these two regions is fairly representative. The coverage of the stratigraphic column is less satisfactory. Far more work has been done on Recent and Pleistocene deposits than on the older strata. It was necessary, therefore, to group some of the older periods in order to obtain a sufficient record for statistical treatment. The problem of sedimentary environments is less satisfactorily answered. No doubt the Recent and Pleistocene sediments of both Europe and the United States are markedly affected by glacial contributions. These raise the frequency of some mineral species in an unusual degree. While the effect of glacial contributions cannot be disregarded, it seems probable that the records of nonglaciated areas demonstrate, nevertheless, a greater mineral complexity for Recent sediments.

MINERAL PERSISTENCE AND GEOLOGIC AGE

It is apparent from a study of the persistence chart (Fig. 1) that some minerals, notably zircon and tourmaline, show almost no change in frequency of occurrence with decreasing age. Others, also present in sediments of all ages, show an increase in number of times reported with decreasing age. Some of these, such as garnet

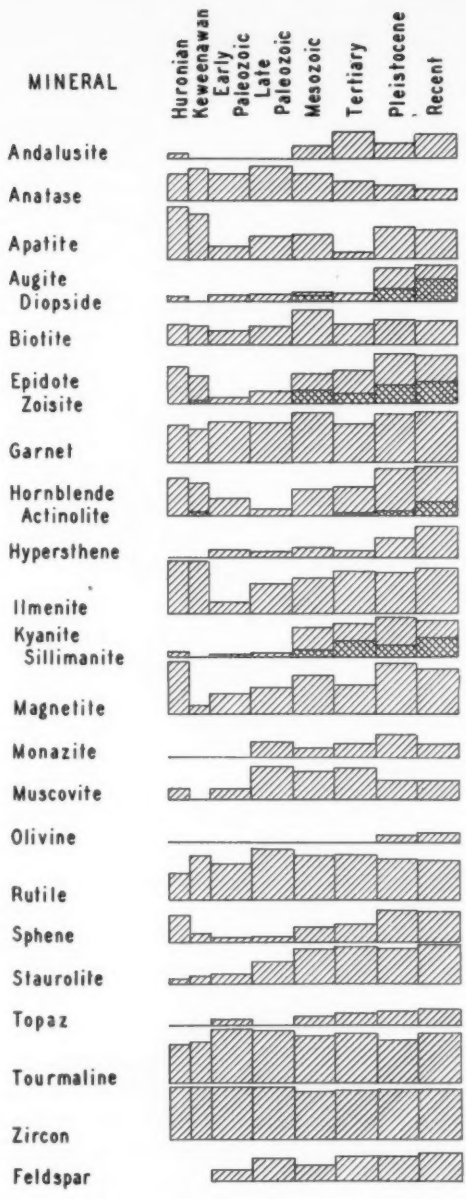

FIG. 1.—Frequency of Occurrence Chart. Based on Table 1

and biotite, show but a feeble increase, while others—notably epidote, hornblende, magnetite, ilmenite, staurolite, sphene, and feldspar—show marked increase. Some minerals are absent in the older deposits and make their appearance late in time and then increase toward the present. In this category fall andalusite, sillimanite, and zoisite. A few, like olivine, occur only in Recent and Pleistocene deposits.

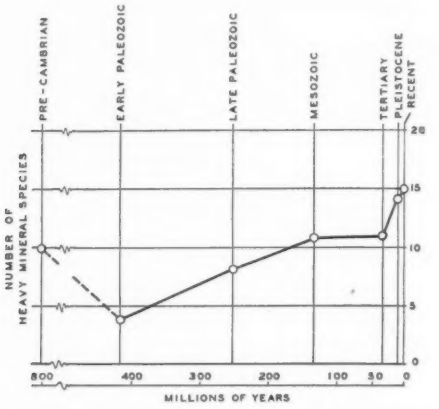

FIG. 2.—Number of heavy-mineral species and age of deposit. The number of species in *more* than half of the reported formations is plotted against the age of the beds investigated. Based on Table 1.

A "negative" persistence is suggested for several minerals. These minerals are more commonly reported from older sediments than from younger deposits. Anatase, in particular, shows a marked decline in frequency of occurrence with decreasing age of the deposit. Rutile shows the same decrease but to a lesser degree. The muscovite record is less clear but possibly also demonstrates a negative persistence.

The pre-Cambrian record, especially the pre-Keweenawan, is anomalous because of the formation *in situ* by metamorphic processes of many mineral species, notably epidote, hornblende, and sphene. The excess of magnetite and ilmenite in the pre-Cambrian is in part due to the assumption that the opaques reported consisted of these two minerals. This is only partly correct.

Inspection of either the table or the persistence diagram shows the increasing complexity in the younger sediments. If the species reported in more than half of the investigated formations of each time period be counted, an increase from 4 in early Paleozoic time to 15

TABLE 2

INDEX NUMBERS OF ABUNDANCE
(Recent = 100)

No.	Mineral	Pre-Keweenawan	Keweenawan	Early Paleozoic	Late Paleozoic	Mesozoic	Tertiary	Pleistocene	Recent
1	actinolite	0	31	12	15	12	27	31	100
2	anatase	250	310	250	325	250	180	140	100
3	andalusite	22	0	0	4	58	109	84	100
4	apatite	189	160	43	85	89	21	111	100
5	augite	15	0	18	21	27	24	93	100
6	biotite	70	67	51	65	116	70	103	100
7	diopside	0	0	7	5	30	7	54	100
8	epidote	76	59	13	26	63	66	103	100
9	garnet	74	65	83	80	100	77	97	100
10	hornblende	76	67	35	13	54	59	98	100
11	hypersthene	0	0	26	21	31	22	62	100
12	ilmenite	120	120	25	69	80	95	93	100
13	kyanite	14	0	9	11	83	90	110	100
14	magnetite	118	18	45	60	84	62	112	100
15	monazite	0	0	12	116	72	96	164	100
16	muscovite	53	0	55	166	145	160	100	100
17	olivine	0	0	0	0	0	0	72	100
18	rutile	67	113	91	128	112	113	103	100
19	sillimanite	0	0	0	0	35	81	62	100
20	sphene	66	26	11	17	45	57	102	100
21	staurolite	13	19	23	56	86	92	90	100
22	topaz	0	0	32	0	57	75	93	100
23	tourmaline	75	83	107	105	96	101	86	100
24	zircon	105	105	105	105	97	98	100	100
25	zoisite and clinozoisite	0	19	0	10	57	48	86	100
26	feldspar	.....	.....	40	81	60	87	87	100

in the Recent is at once apparent. The data for all investigated periods are shown graphically in Figure 2. The increase in complexity is greatest in later times, so that the curve rises steeply in Pleistocene and Recent times.

Finally, from the data assembled, an "order of persistence" may

be worked out. This is obtained by adding together the frequencies of occurrence in all the time groups (except the pre-Cambrian) for each mineral species. Some minerals, however, are rarer than others, even in Recent deposits. To compensate for this inequality of abundance, index numbers were used. The base period was the Recent, hence the frequency of each species in that period was raised to 100, and that in each of the several older periods was multiplied by a factor which is the ratio of 100 to the observed frequency of occurrence in Recent deposit (Table 2). Andalusite, for example, had a frequency of occurrence in Recent deposits of but 45 per cent. Hence the reported frequencies for the other time periods were all multiplied by the factor 2.22—the ratio of 100 to 45. The order of persistence is as follows:

−3 anatase	10 kyanite
−2 muscovite	11 epidote
−1 rutile	12 hornblende
	13 andalusite
1 zircon	14 topaz
2 tourmaline	15 sphene
3 monazite	16 zoisite
4 garnet	17 augite
5 biotite	18 sillimanite
6 apatite	19 hypersthene
7 ilmenite	20 diopside
8 magnetite	21 actinolite
9 staurolite	22 olivine

The order of persistence is in general accord with opinions held by most investigators. Thoulet's "order of destruction" was olivine, pyroxenes, amphiboles, apatite, feldspar, biotite, muscovite, quartz, rutile, zircon, and corundum. In so far as these minerals occur in the persistence series, it can be seen that they are all in proper order, except for the inverted position of rutile and zircon. The "stability series" of Goldich is muscovite, biotite, hornblende, augite, hypersthene,[4] and olivine. These minerals are in the same order in this series as they are in the persistence series.

[4] Goldich omitted hypersthene, but, since it occurs in the reaction series in the position indicated and since Goldich believed the stability series to be the reverse of the reaction series, it has been added.

Surprising, perhaps, is the position of apatite. The position of this mineral confirms Thoulet's estimate but is opposed to that of H. B. Milner, who considers apatite unstable. Milner[5] also differs

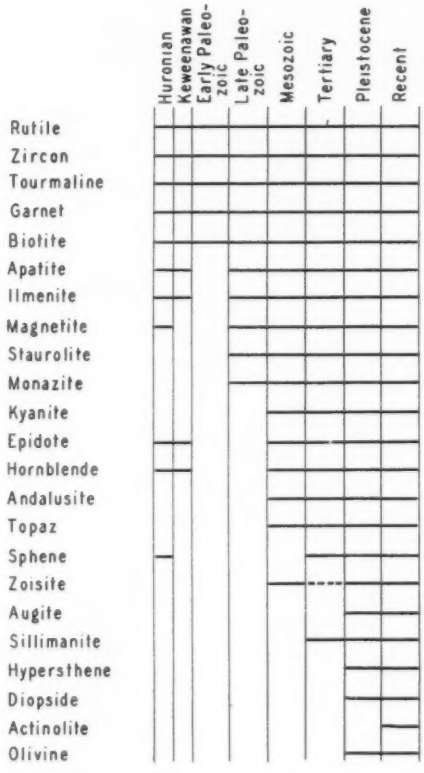

FIG. 3.—Mineral persistence chart. Line indicates presence of mineral in *relative* frequency (Recent = 100) of 50 or greater. Based on Table 2.

from the writer in that he considers magnetite more stable than ilmenite, and in other particulars as well. The writer is confident, however, that the position of the more common minerals is well

[5] *Sedimentary Petrography* (3d ed.; London: Thos. Murby & Co., 1940), p. 499.

established.[6] The positions of the rarer minerals are subject to some revision, since the probable error involved in their frequency of occurrence is large.

DISCUSSION

COMPLEXITY OF SUITE

The two possible reasons for the increasing complexity or "richness" of the mineral suite with decreasing age are (1) progressive increase in complexity of the terrane from which the sediments were derived and (2) loss of less stable minerals by intrastratal solution. The first possible explanation seems to be the less probable one. Several reasons support this view. No doubt each geologic revolution is accompanied by the invasion of the upper crust by magma and by dynamic and thermal metamorphism. Such activity yields new rocks later to be unroofed by erosion and to shed new material to the basins of sedimentation. There is not much evidence to show that these successively younger crystalline source rocks are fundamentally different from those of ancient date. If simplicity of mineral suite is a consequence of re-working older sediments and further elimination of the less stable minerals by abrasion and weathering, why, then, should not sediments become progressively simpler with decreasing age since the newer sediments should contain a larger proportion of re-worked material? Just the reverse is true. It is not reasonable to believe that the older, mineralogically simpler sediments should all be re-worked sediments, while only the Tertiary and

[6] Since this paper was written, Smithson ("The Alteration of Detrital Minerals in the Mesozoic Rocks of Yorkshire," *Geol. Mag.*, Vol. LXXVIII [1941], pp. 97–112) has published on the stability of certain minerals in Triassic and Jurassic rocks. His order is as follows:

Stable	zircon, rutile, tourmaline, apatite
Somewhat stable	monazite
Unstable	garnet, staurolite, kyanite
Very unstable	ferromagnesian minerals, etc.

It is apparent that this list is in rough agreement with that of the writer. Significant, too, are the high stability ratings given both monazite and apatite.

later sediments are first-cycle deposits. More probably the mineralogical simplicity of the older deposits is due to intrastratal solution.

The correctness of the hypothesis of intrastratal solution is best demonstrated by the persistence order of the important rock-making ferromagnesian minerals. The order is—in reverse order of persistence—(1) olivine, (2) hypersthene, (3) augite, (4) hornblende, (5) biotite, and (6) muscovite. This order is precisely that given by Goldich in his stability series. Since the position in the stability series is a measure of susceptibility to weathering, it seems very improbable that the order of persistence based on the geologic record can mean anything except loss by solution following deposition. Only by the most improbable coincidence can their persistence order be otherwise explained.

Direct evidence of intrastratal solution of even the more stable species has often been described. Etched garnet[7] is often reported as is also etched staurolite. The "hicksaw" and "cockscomb" phenomena displayed by augite, hypersthene, and hornblende have been commented on by several authors[8] and have been shown by C. S. Ross, H. D. Miser, and L. W. Stephenson[9] to be due to post-depositional solution.

F. Smithson,[10] moreover, has shown that the richness of the suite, even in the different parts of the *same* formation, is a function of post-depositional changes rather than an original character. The richness of the suite is inversely related to the authigenic features of the deposit. Where authigenic changes—outgrowths on zircon, etc.—are most prominent, the suite is impoverished; where the authigenic action is feeble, the suite shows a maximum variety of species. These

[7] M. N. Bramlette, "Natural Etching of Detrital Garnet," *Amer. Min.*, Vol. XIV (1929), pp. 336–37.

[8] C. H. Edelman, "Diagenetische Umwandlungerscheinungen an detritischen Pyroxenen und Amphibolen," *Fortschr. Min. Kryst. Pet.*, Vol. XVI (1931), pp. 323–24; C. H. Edelman and D. J. Doeglas, "Reliktstrukturen detritischer Pyroxene und Amphibole," *Min. Pet. Mitt.*, Vol. XLII (1932), pp. 482–90.

[9] "Water-laid Volcanic Rocks of Early Upper Cretaceous Age in Southwestern Arkansas, Southeastern Oklahoma, and Northeastern Texas," *U.S. Geol. Surv. Prof. Paper 154-F* (1929), pp. 175–202.

[10] "Statistical Methods in Sedimentary Petrology," *Geol. Mag.*, Vol. LXXVI (1929), pp. 417–27.

antipathetic relations strongly suggest a causal relation between the chemical activity responsible for authigenic growth and solution of the less stable minerals.

Analogous reciprocal relations appear in the data here tabulated. Anatase is both detrital and authigenic, but since it has a marked negative persistence, it is usually authigenic. The older the deposit, the more probable is its formation. Since it bears a reciprocal relation to sphene, it seems likely that it forms at the expense of this mineral. This relation has been confirmed by P. G. H. Boswell,[11] who noted a similar reciprocal relationship in the frequencies of these two minerals in the various beds of the same age. In deposits of the earlier periods, where anatase is most frequently reported, the associated mineral suite is most restricted in composition.

As a corollary to the conclusions reached above, it should be noted that an impoverished mineral assemblage—such as characterizes the Paleozoic rocks—does not necessarily mean derivation from ancient pre-existing sediments but may mean only that the deposit is of great age and has lost the less stable species by intrastratal solution.

STABILITY OF MINERALS

The stability of minerals depends on a number of factors. Goldich formulated his stability series after a careful study of mineral and chemical changes observed in weathering. He pointed out the relation between the position of the mineral in the stability series and its corresponding position in Bowen's reaction series. Minerals formed at highest temperatures in the most anhydrous magmas are less stable under surface conditions than those formed under lower temperatures in the more hydrous end magmas. The order of persistence determined by statistical summary of the literature enables us to extend the stability series to include many species not studied by Goldich or involved in the reaction principle.

Secondary enlargement is a self-evident criterion of stability just as etched surfaces, etc., are a criterion of instability. Even tourmaline and zircon—the two most stable detrital minerals—exhibit secondary outgrowths. The alkali feldspars, on which persistence

[11] "Petrography of the Sands of the Lias-Inferior Oölite of the West of England," *Geol. Mag.*, Vol. LXI (1924), pp. 246–64.

data are incomplete, presumably would rank high in stability if the secondary-growth criterion is reliable. The reports on feldspar were found sufficiently numerous to justify plotting its frequency of occurrence (Fig. 1). This confirms its high stability. It would be number nine in the stability series. Since quartz is commonly secondarily enlarged, it too should have a high stability. Its ubiquitous nature confirms this conclusion. If, however, the frosted appearance of the quartz in some of the older sandstones is due to solution and is the visual expression of a fine etching (analogous to that produced on glass by hydrofluoric acid), then quartz is not wholly stable. It is never deeply etched, as is garnet, and therefore ranks higher in stability than that very stable mineral.

The negative persistence of a few species, that is, those more abundant in the older deposits than the Recent, is due partly to oversight and partly to authigenic formation. A little zircon and tourmaline, for example, may well be overlooked in the amphibole- and pyroxene-rich glacial suites of the Pleistocene and the Recent sediments derived therefrom. Anatase, on the other hand, may be more frequently reported from the older sediments, because it is largely authigenic. The possibilities for its formation are enhanced with passage of time. In like manner, rutile seems to be authigenic in so many cases that it, too, is slightly more common in the older deposits than in the Recent. The apparent negative persistence of muscovite is less clear, owing perhaps to the uncertain position of muscovite. It was regarded as a light mineral by many investigators.

Boswell has noted a relationship between density and stability of the several forms of composition. Kyanite is both denser and more persistent than either sillimanite or andalusite. Rutile is likewise denser and more persistent than anatase or brookite.

That some minerals have a limited persistence in the geologic record has been noted before. H. H. Thomas,[12] for example, calls attention to the absence of andalusite in older beds and believes that it could survive only for a limited period in sediments. This paper is an attempt to extend this observation of Thomas and others to many more mineral species.

[12] "Detrital Andalusite in Tertiary and Post-Tertiary Sands," *Min. Mag.*, Vol. XV (1909), pp. 241–44.

APPLICATIONS

In a general way it should be possible to determine the geologic age of a formation by a consideration of both number and kind of the heavy minerals independently of fossil content or stratigraphic relations. At present this possibility has only theoretical interest, since many other factors than age govern the presence or absence of a particular mineral species.

FIG. 4.—Mineral persistence in formations of Big Horn Basin (after M. H. Stow)

Whether a mineral survives intrastratal solution depends on the nature of the mineral, the pH of the interstitial solutions, the permeability of the bed and the velocity of flow of the ground waters, the temperature, and the geologic age of the deposit. In this study only the first and last factors were investigated. The results are, therefore, an average only and not strictly applicable to particular formations or basins of deposition. In a "sealed environment," for example, minerals with low stability may survive longer than more stable species in younger deposits through which a strong flow may have taken place. The order of survival in any given sequence would be the same as the general order here established.

In a study of Cretaceous and Tertiary formations in the Big Horn Basin in Wyoming, M. H. Stow[13] recorded both the relative abundance and the persistence of certain heavy minerals. Figure 4, made from data given by Stow, shows that the order of persistence in this particular section is the same as that worked out by the writer. Stow, however, interprets the appearance of staurolite and kyanite and, particularly, hornblende as a record of new sources of supply. Since the order of appearance is the reverse of that of mineral stability, it seems possible that the order is due to survival ability.

Some writers have noted mineral gradients in ancient deposits. These gradients are in part related to regional dip. The decrease in frequency of some species in a downdip direction (toward the axis of the basin of deposition) and the concomitant increase of other species should be viewed with caution. If one mineral, such as epidote, declines downdip and another, such as garnet, increases, it may be due to loss of the less stable species by solution under the greater cover of sediments (and hence higher temperatures and more active solution) and a *relative* increase of the more stable species.

[13] "Dating Cretaceous-Eocene Tectonic Movements in Big Horn Basin by Heavy Minerals," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 731–62.

OZARK SEGMENT OF MISSISSIPPI RIVER[1]

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ABSTRACT

The well-defined trench of the Mississippi River between St. Louis and Cape Girardeau roughly contours the eastern slope of the Ozark topographic dome instead of following the lowland farther east in Illinois. This relationship is believed to result from upwarping of the dome after the river had assumed essentially its present course—in other words, the Mississippi is thought to be antecedent to the warping.

Strath-terrace remnants in tributary streams indicate two movements separated by a time of quiescence. Evidence now available does not date the warping closely. The movements appear to have been post-Wilcox and preglacial.

THE PROBLEM OUTLINED

It was first announced by C. F. Marbut[2] that the hilltops in southeastern Missouri are remnants of a former peneplain with monadnocks and that this surface has been warped up to form a topographic dome. This is the Ozark topographic dome. It occupies approximately the same areal position as the Ozark structural dome plainly indicated on any geologic map of the region.

The Mississippi River has a curious relationship to the Ozark topographic dome. Upstream from St. Louis the river is incised into a glaciated plains country, where its course has been determined at least in part by the former positions of the margins of ice sheets. Downstream from the vicinity of Cape Girardeau the present course of the river follows the axis of the Gulf embayment synclinal trough. But in the intervening country, through a segment 100 miles long, the river cuts across the eastern flank of the topographic dome instead of following around its base (Fig. 1).

E. W. Shaw[3] recognized this apparent anomaly. He wrote: "The position of the Mississippi River shows lack of adjustment, for it flows on the side of a trough, both structural and physiographic. The

[1] Published with the permission of the director of the Missouri Geological Survey.

[2] "Surface Features of Missouri," *Mo. Geol. Surv.*, Vol. X (1896), pp. 11–109.

[3] "Quaternary Deformation in Southern Illinois and Southeastern Missouri" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XXVI (1915), p. 68.

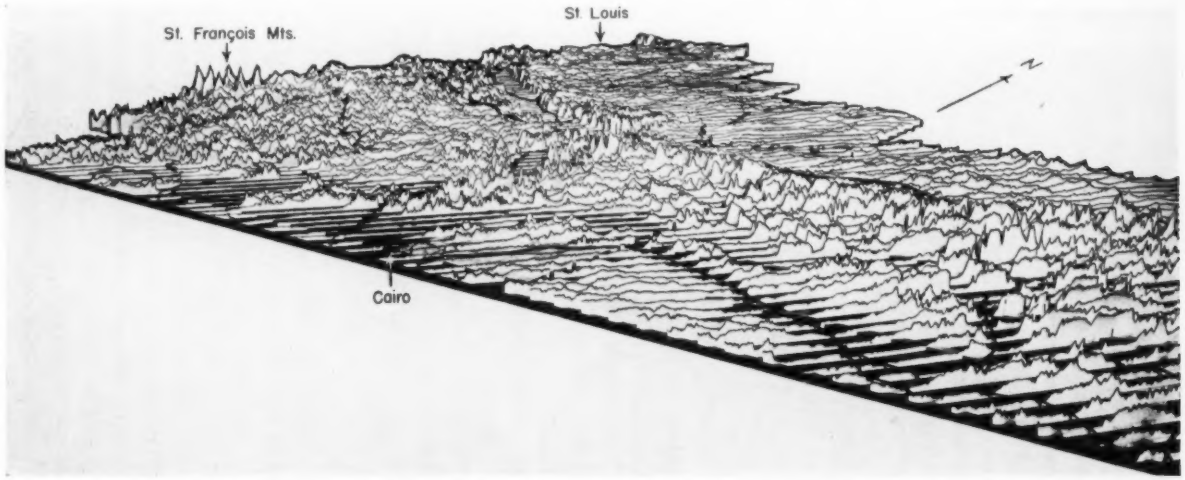

FIG. 1.—Ozark segment of Mississippi River and its environs, shown by profiles. Length of nearest edge of block, about 100 miles. Vertical scale, ×33. The position of the river trench transecting the flank of the Ozark topographic dome is clearly apparent.

The area represented is that of the U.S. Geological Survey topographic quadrangles shown in Fig. 2. Lines were drawn from the southwest corners to the northeast corners of the maps, and other lines were drawn parallel to these, intersecting the north-south margins of each map at intervals of 2′30″ of latitude. This resulted in a series of parallel lines, spaced approximately 1.8 miles apart, trending southwest-northeast across the entire area. Along these lines profiles of the surface were drawn on quadrille-ruled strips of bristol board with the contours (interval 20 feet) as vertical control and with a vertical exaggeration of 33×. The maps were glued to a suitably shaped base-board which was next precision-groooved along the profile lines. The Bristol-board strips, cut out along the profiles, were then set up vertically in their proper positions. Dark-colored ribbons were laid upon the surface in the positions of the chief streams, and a ribbon was added to represent an inferred glacial-drift border (cf. Fig. 3). (Profiles constructed principally by L. G. James.)

natural place for the river between St. Louis and Cairo is in the low, soft-rock country 50 miles or more east of its present position. . . . ."

Shaw described the river's course as occupying the side of a trough rather than the flank of a dome, because he approached the problem from the broad syncline in Illinois east of the river instead of from the anticlinal Ozark highland west of the river.

Study of the areal geology of parts of Perry and Cape Girardeau counties, Missouri, many years ago led the writer to speculate on the factors that determined the location of the river in that region. These factors, implicit also in Shaw's statement, constitute the problem to be discussed: Why does the Ozark segment of the Mississippi River cut through the Ozark topographic dome instead of detouring it?

CAUSE OF RELATION OF RIVER TO DOME

In this segment the immediate valley of the Mississippi, trending generally southeast, is a well-defined trench (Figs. 1 and 3) averaging about 5 miles in width. It is limited by steep bluffs, 100–300 feet high, cut into Paleozoic strata that have a regional gentle northeast-to-east dip. Through the first 60 miles downstream from St. Louis the trench is oblique to the strike of these rocks. Through the next 25 miles (between Chester, Illinois, and Cape Cinque Hommes, Missouri) it parallels the strike as well as a narrow belt of complex faulting. At Cape Cinque Hommes it turns south across the fault belt and approximately follows a north-south strike to the point where it emerges onto the broad surface of the Gulf embayment.

HYPOTHESES OF CONSEQUENT, SUBSEQUENT, AND SUPERPOSED ORIGIN

It is immediately evident that the Ozark segment of the Mississippi River did not originate as a stream consequent upon the present surface, because it either contours or forms a chord across the Ozark topographic dome. Nor can it be regarded as a subsequent stream that has grown headward along a belt or belts of weak rock, because it cuts across lithologic belts and a belt of complex faulting and avoids an obvious subsequent route underlain by nonresistant Ordovician limestones that extend northwest through 35 miles from near Cape Girardeau. Further, it can scarcely be thought of as super-

posed from an unconformable cover. Such a cover would have had to be 200–300 feet thick in the lowland east of the river, in order to permit the river to flow unimpeded across the part of the Ozark dome

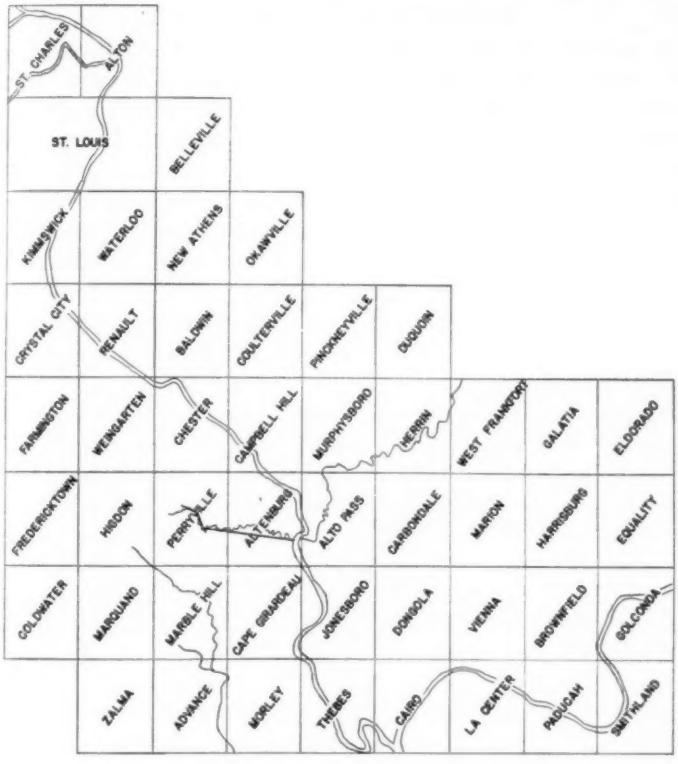

FIG. 2.—Index map showing positions of U.S. Geological Survey topographic quadrangles from which the profiles in Fig. 1 were constructed. The broad line in the Perryville and Altenburg quadrangles indicates the position of the profile shown in Fig. 4.

that must have been buried by any such cover. No remnants that could be referred to such an unconformable blanket have been reported.

Two further hypotheses, however, demand more detailed con-

sideration: that the river was localized by the margin of one of the Pleistocene ice sheets, and, alternatively, that it is antecedent to late uplift or uplifts of the Ozark dome.

HYPOTHESIS OF AN ICE-MARGIN STREAM

It has been known for many years that long stream segments in the Mississippi River drainage system originated through the blocking of preglacial valleys by ice sheets. During the process the former drainage, augmented by meltwater, was obliged to run off laterally, along rather than down the regional slope. Notable among such stream segments are parts of the Ohio, parts of the Missouri, and parts of the upper Mississippi. The Ozark segment of the Mississippi contours the slope, and much of it lies parallel with, and very close to, the western limit of the glacial drift (Fig. 3). Because of these facts this part of the river might seem to have originated under control of the margin of a glacier. However, this hypothesis meets the following objections:

1. If a preglacial Mississippi River had been "pushed" westward by an ice sheet as the glacier advanced up the east-facing Ozark slope, the tributaries flowing from the west must have been ponded up to the height of the brink of the present Mississippi trench. Their postglacial courses should be incised into fills made during this ponding. No remnants of such thick fills have been found. The present fill remnants in the mouths of the tributary valleys lie 100–300 feet below the brink of the trench, occur at accordant elevations in the valleys of the eastern tributaries as well as in those on the west, and form a distinct and consistent profile (and possibly a second less distinct profile) sloping down the Mississippi. The sediments actually present appear to be remnants of former outwash deposits derived from up the Mississippi and augmented by contributions from tributary streams that were slackened by the rising fill in the main valley. Shaw[4] shows that one of them, at least, is of Wisconsin age.

2. If the river had been permanently displaced by an ice sheet, a capacious preglacial valley now filled with drift should lie essentially

[4] "Newly Discovered Beds of Extinct Lakes in Southern and Western Illinois," *Ill. Geol. Surv. Bull. 20* (1915), p. 154. See also P. Robertson, *Trans. Acad. Sci. of St. Louis*, Vol. XXIX (1938), pp. 172–86.

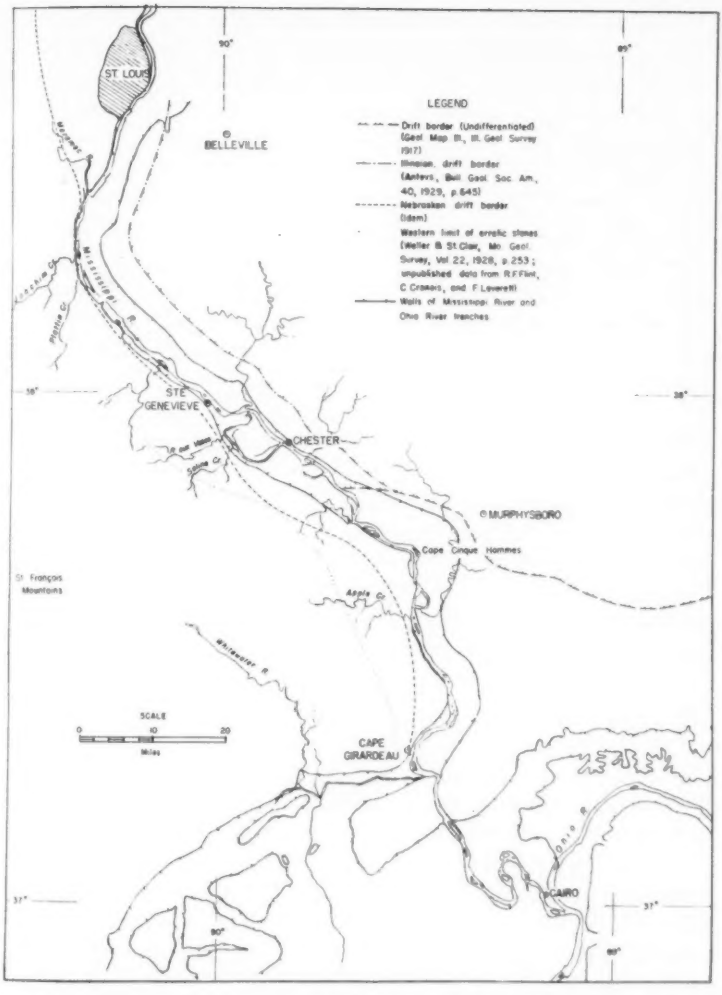

FIG. 3.—Sketch map showing Mississippi River channel and trench, inferred glacial drift borders, and locations of places and features referred to in the text.

parallel with the Mississippi and 50 miles or more east of it, occupying the broad synclinal lowland of southern Illinois. This valley should be connected at its northern and southern ends with the present Mississippi trench. So far as the writer is aware, no borings or other operations in southern Illinois have revealed the presence of any large buried valley in this region.

3. If the preglacial Mississippi lay east of its present route, the tributary valleys leading east down the slope of the Ozark dome to the Mississippi should have continuations east of the present Mississippi trench, leading to the preglacial master-valley. These continuations should now either be buried or have reversed drainage. If such valleys existed, they would be exposed in section in the eastern wall of the Mississippi trench. The only gaps in the wall are made by normal tributaries, and the bedrock closures toward their headwaters are not such as to admit of former drainage in the reverse direction.[5]

4. The form and relief of the bedrock surface buried beneath the Illinoian drift are closely similar to the configuration of the surface south of the Illinoian drift border. This shows that the region had reached nearly its present state of dissection under the control of the Mississippi in its present position prior to at least the Illinoian glacial age.

5. In the river bluff at Little Rock near Ste Genevieve, Missouri, till is exposed less than 50 feet above the river[6] and 100 feet below the immediate brink of the trench, which is low at this place. Therefore, excavation of the Mississippi trench to at least this depth must have occurred prior to the glaciation (believed to be either Illinoian or Kansan) responsible for the till.

6. The limit of more or less continuous drift leaves the Mississippi trench a few miles south of Chester, Illinois, and swings east across southern Illinois (Fig. 3). If this sheet of continuous drift were the only drift in the region, this sharp divergence of its border from the path of the Mississippi would constitute conclusive evidence against ice-margin control of the Mississippi. However, numerous erratic

[5] Shaw, "Quaternary deformation . . . . ," *op. cit.*, p. 67.

[6] S. Weller and S. St. Clair, "Geology of Ste Genevieve County, Missouri," *Mo. Bur. Geol. and Mines*, Vol. XXII (1928), p. 252.

stones and boulders of igneous and metamorphic rock types are present west of the trench throughout a belt varying up to many miles in width and reaching high elevations. The writer has found one 8 miles west of the river and 18 miles south of the mapped position of the continuous drift border at an elevation 230 feet higher than present mean low water in the same latitude, and Frank Leverett[7] has found two more on the western brink of the Mississippi trench at Cape Girardeau, 15 miles still farther south. If these stones were deposited by a glacier, then the entire Ozark segment of the Mississippi can be said to lie close to a drift border. Nevertheless, this matter carries little weight in view of the apparently conclusive character of points 1, 2, and 3 above.

HYPOTHESIS OF AN ANTECEDENT STREAM

One hypothesis remains—that the Mississippi River in this region is antecedent to the upwarping of the Ozark dome that has brought this structure into its present topographic prominence. According to this hypothesis, the Mississippi was flowing upon the erosion surface represented by the present hilltops; and, as the upbowing proceeded, the river maintained its course. The evidence supporting this view consists of the anomalous position of the stream plus the evidence cited against the alternative hypotheses; and, taken together, these point to the strong probability that the position of the Mississippi trench is the result of gentle doming at some time or times after the river had become located in its present position.

The present inquiry is not aimed at discovery of the factors that determined the location of the river prior to the doming. The river may have been superposed across beveled Paleozoic rocks from an unconformable cover of younger fluvial or marine sediments. It may have been consequent on some downwarp that continued the synclinal structure of the Gulf embayment toward the northwest. It may have been located in part by a series of lithologic and structural controls. Postdoming erosion has been so great, and remnants of preglacial gravel deposits along the trench are so meager, that at present there is no reliable factual basis for selection among these or other possibilities.

[7] Unpublished communication.

THE OSAGE RIVER

The hypothesis that the Ozark segment of the Mississippi is antecedent to the rise of the Ozark topographic dome is supported by the analogy of the Osage River, which cuts across the northwest flank of the Ozark dome just as the Mississippi cuts across its eastern flank. The Osage originates in Kansas and flows east across western Missouri toward the Ozark dome. As pointed out by W. A. Tarr,[8] the meanders of this stream are open or free, as far downstream as a point in St. Clair County. Here they become incised, the depth of incision increasing to a maximum of 300 feet in Linn County and then diminishing to 150 feet where the Osage empties into the Missouri River. From St. Clair County to its mouth the Osage is within the area of the Ozark dome, and in Linn County it is "farthest up" on the dome. Tarr concludes that the Osage is antecedent to the topographic dome.

The depth of incision of meanders, used by Tarr as evidence of the antecedent character of the Osage, cannot be used in the case of the Mississippi, which meanders freely on the thick alluvium that partly fills its trench. Whether or not the preglacial Mississippi had incised meanders is not known. If it did, the great volume of sediment-laden meltwater that poured down the river during the glacial ages undermined the bluffs to so great an extent that the valley was expanded to the wide, open trench of today.

OZARK TOPOGRAPHIC DOME

CUESTAS AND LOWLANDS

The conclusion that the Mississippi is antecedent to upwarping of the Ozark dome demands further inquiry into the features of the domed surface as a basis for an inquiry into the character and date of the doming.

The domed surface has been adequately described by Marbut, and for the present purpose little need be added to his account. The general elevation at the summit in the St. François Mountains is about 1,300 feet. The radial slope varies with the direction, being 8–

[8] "Intrenched and Incised Meanders of Some Streams on the Northern Slope of the Ozark Plateau in Missouri," *Jour. Geol.*, Vol. XXXII (1924), pp. 594–97.

10 feet per mile toward the northwest, 12–16 feet per mile toward the southeast, and about 20 feet per mile toward the east, at least through the first 25 miles outward from the summit. The surface is represented to northwest and southeast by the tops of closely spaced hills (Fig. 1) cut from strata that dip only slightly more steeply than the slope of the hilltop surface. To the east the dips are steeper; in consequence, the strata form a succession of alternating cuestas and lowlands. The principal cuestas are formed from west to east by the Potosi dolomite, the St. Peter sandstone, the Bailey limestone, certain Lower Mississippian formations (chiefly the Burlington limestone), and in Illinois by the sandstone members of the Pottsville formation. The limestones and the dolomite constitute resistant cap rocks, because they are very cherty. None of the cuestas is wholly continuous, because the outcrops of all the strata mentioned are interrupted by faults.

The lower lands between the cuestas are underlain by less cherty limestones and dolomites and by shales. The most conspicuous of these areas is underlain by Ordovician limestones of Plattin and younger age, where solution has been important in lowering the surface, locally developing karst topography.

Profiles drawn at right angles to the strike of the cuestas fail to reveal facets at the cuesta summits, from which it could be directly inferred that the cuestas had been left standing by etching away of the weak rocks during rejuvenation of a broad erosion surface. However, the cuesta summits fall into the radially sloping surface widely represented by hilltops farther west, and therefore it appears probable that these summits stand close below the position of the former erosion surface.

The irregularity of the hilltop surface may result from several causes:

1. Incomplete reduction of the surface before it was rejuvenated. This is certainly the explanation of the conspicuous monadnocks. Probably it also explains some of the less conspicuous irregularities.

2. Differential reduction of remnants of the surface since its rejuvenation began. In view of the absence of recognizable facets on the cuesta summits, this seems probable, but there appears to be no basis for recognizing it in any one part of the surface.

3. Differential local movements of the crust since the surface was completed. G. W. Rust[9] suggests that the high area in southwestern Ste Genevieve County may record such movement.

STREAM PATTERN

Although the Meramec River system northwest of the Ozark dome crest exhibits pronounced asymmetry that strongly suggests the influence of domelike warping, the pattern of the streams tributary to the Mississippi on the east flank of the dome yields little information. These streams are small and, with local exceptions, are radial to the dome. The exceptions are stream segments that have become adjusted to belts of weak rocks between the cuestas. Whitewater River in Cape Girardeau County and the South Fork of Saline Creek in Perry County are examples.

The lower courses of the larger streams (River aux Vases, Saline Creek, and Apple Creek) on the east flank of the dome have incised meanders; the smaller streams lack this feature. The meanders indicate merely that the larger streams, prior to rejuvenation, occupied strath valleys in which they were probably at grade.

VALLEY PROFILES

With the exception of Joachim and Plattin creeks, the valleys on the east flank of the dome have remnants of strath terraces. These are best developed in the valley of Apple Creek, the largest of the streams, and are shown in Figure 4. The remnants form a fairly consistent single profile. Not only does the profile as a whole bevel the structure, but at one locality (SE. $\frac{1}{4}$, Sec. 34, T. 34 N., R. 11 E.) a single remnant on a broad meander spur truncates both the St. Peter sandstone and the Joachim dolomite. This establishes the divergent relation between the terrace profile and the dip of the strata and proves that the terrace along Apple Creek is not controlled by lithology. Toward the mouth of Apple Creek the terrace remnants pass beneath a fill that is related to Wisconsin(?) outwash in the Mississippi Valley; hence the terrace antedates this Pleistocene glacial age.

The presence of the strath terrace between the hilltop surface and the modern stream profile indicates that the rejuvenation of the

[9] "Preliminary Notes on Explosive Volcanism in Southeastern Missouri," *Jour. Geol.*, Vol. XLV (1937), p. 55.

valley of Apple Creek took place in two phases separated by a pause. The strath-terrace remnants in the smaller valleys between Apple Creek and the Meramec River are approximately as high above the present stream profiles as are those of Apple Creek, suggesting that the two-phase rejuvenation was common to the east flank of the Ozark dome. A single strath terrace has been observed in other stream valleys on both northern and southern flanks of the dome: by O. H. Hershey[10] and Marbut[11] in many Ozark valleys, by W. Lee[12] in the Gasconade and Meramec river systems, by J. Bridge[13] in the

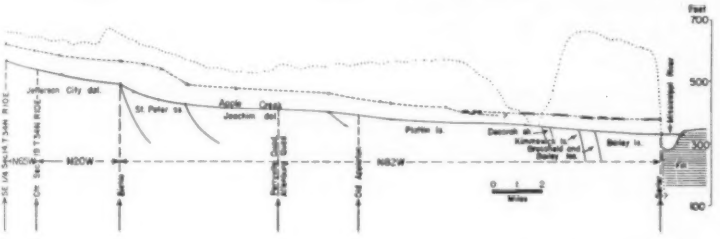

FIG. 4.—Profiles along Apple Creek, along the line in the Perryville and Altenburg quadrangles shown in Fig. 2.

Continuous line = profile of Apple Creek. Dashed line = profile of strath-terrace remnants, located at points marked *x*. Wide lines with serifs = fill-terrace remnants near mouth of Apple Creek. Dotted line = hilltop surface (generalized). Stratigraphy and structure (with greatly exaggerated dips) are indicated.

Current River system, by J. S. Cullison[14] in the White River system and by the writer in the valley of Whitewater River. These occurrences increase the probability that all the valleys were rejuvenated more or less contemporaneously by a movement that affected streams on at least three flanks of the Ozark dome. Such a movement could only have been domelike in character. If the domelike form of

[10] "River Valleys of the Ozark Plateau," *Amer. Geol.*, Vol. XVI (1895), pp. 342–44.

[11] "Geology of Morgan County (Missouri)," *Mo. Bur. Geol. and Mines*, Vol. VII (1908), pp. 8–9.

[12] "The Geology of the Rolla Quadrangle (Missouri)," *Mo. Bur. Geol. and Mines*, Vol. XII (1914), pp. 52–58.

[13] "Geology of the Eminence and Cardareva Quadrangles (Missouri), *Mo. Bur. Geol. and Mines*, Vol. XXIV (1930), pp. 30–32, 53–54.

[14] Unpublished communication.

the hilltop surface is considered in this connection, the probability becomes strong that the Ozark dome has been rejuvenated twice during late geologic time, the pause between the rejuvenating movements being represented by the strath terrace present in the larger valleys.

The long profiles of valley floors on the east flank of the dome give little aid to this inquiry. Plotted on the existing topographic maps with contour lines (20-foot interval) as controls, they show no convexities other than those evidently related to belts of resistant rocks crossed by the streams. Apple Creek exhibits a convexity of this type where it crosses the St. Peter sandstone and another, very faint, convexity where it passes from the Joachim dolomite to the Plattin limestone. Absence of convexities other than lithologic is expectable in streams radial to an active dome. All points on the long profile of each would be raised simultaneously with respect to points downstream, and this would result not in localized incision progressing up the valley but in simultaneous incision all along the profile.

However, Shaw[15] has found that in valleys tributary to the Mississippi in southern Illinois, well records indicate that the bedrock floors of the valleys beneath Pleistocene valley fills rise in the downstream direction, that is, toward the Ozark dome. Shaw infers that this anomalous relationship is the result of doming of the Ozark region in late Cenozoic time.

The Mississippi trench contains a thick fill of glacial outwash sand and gravel. The bedrock floor is known to lie more than 100 feet below the surface of the river at fourteen points between St. Louis and Cape Girardeau; and at one point, 15 miles south of St. Louis, it lies 277 feet below the river.[16] Data from outside the Ozark segment give depths of the same order of magnitude: 180 feet in the Driftless Area in the latitude of Wisconsin and Iowa,[17] and 100 to

[15] "Quaternary Deformation . . . . ," *op. cit.*, p. 67.

[16] Unpublished communication, U.S. Engineer's Office, St. Louis, 1940. See also Shaw, "Newly Discovered Beds . . . . ," *op. cit.*, pp. 151, 153.

[17] A. C. Trowbridge, "The Erosional History of the Driftless Area," *Iowa Univ. Studies*, Vol. IX (1921), p. 102.

more than 200 feet in the lower Ohio and Tennessee rivers.[18] The floor of the Mississippi trench in the Ozark segment is probably a stream-cut feature, and its deep excavation may possibly date from a time or times when the sea-level was glacially drawn down below its present position. Glacial erosion is not likely to have been an important factor in deepening the trench, because the distribution of the drift shows that only the periphery of the glacier reached the trench and that the movement of the ice was nearly at right angles to the river's course.

If the bedrock floor of the Mississippi trench has the depth inferred in the preceding paragraph, the profiles of the bedrock floors and the strath-terrace remnants in tributary valleys such as the valley of Apple Creek (Fig. 4) must pitch steeply into the Mississippi trench in hanging relationship. The lack of accordance between the bedrock floor beneath the Mississippi and the strath terrace in the tributary indicates that the strath terrace antedates the deepening of the Mississippi.

DATES OF PENEPLANATION AND UPLIFT

Three significant events have been involved in the development of the relations brought out in this discussion: the completion of the virtually peneplaned surface now represented by the hilltops, the rejuvenation that caused the first incision of streams into this surface, and, finally, the second rejuvenation recorded by the strath terraces. The geologic dates of these events are not fixed by the facts now known about the east slope of the Ozarks, and hence their determination goes beyond the scope of this discussion. Study of the problem over a wider area has led to these tentative conclusions:

1. The strath terraces antedate Pleistocene (interglacial?) deepening of the Mississippi trench, and the hilltop surface antedates the drift in southeastern Missouri and southwestern Illinois.

2. The hilltop surface projected southeast across the Advance

[18] L. C. Glenn, "The Geology and Coals of Webster County," *Ky. Geol. Surv., Ser. 6* (1922) pp. 33–34, 122; R. F. Rhoades, "Profiles of the Buried Valleys of the Lower Ohio, Tennessee, and Cumberland Rivers" (abstr.), *Proc. Geol. Soc. Amer., 1936* (1937), p. 97.

Lowland and Crowley's Ridge transects Wilcox (Eocene) strata and is therefore post-Wilcox.

3. The hilltop surface apparently persists across southern Illinois, western Kentucky, and Tennessee, and appears to merge into what has been described as the Highland Rim surface.

4. The post-Wilcox sequence in the Gulf embayment consists of fine-grained deposits with two notable exceptions, the Catahoula sandstone (early Miocene or late Oligocene) and the Citronelle formation (Pliocene and possibly younger). The deposition of these relatively coarse sediments may have been the direct result of upwarping movements of the Ozark dome as well as of other tributary regions, but as yet there appears to be no basis for associating a particular stratigraphic unit with a particular warped surface farther north.

Whatever the exact dates of the warping movements, the essential coincidence of the Ozark topographic dome with the Ozark structural dome indicates that the repeated movements that extend far back into Paleozoic time have a comparatively recent continuation in the persistently positive Ozark region.

CONCLUSIONS

1. The Mississippi River between St. Louis and Cape Girardeau cuts across the eastern flank of the Ozark topographic dome.

2. This segment of the river is believed to be antecedent to the warping that created the dome.

3. Strath-terrace remnants in valleys that drain the eastern slope of the Ozarks into the Mississippi indicate that the warping movement occurred in at least two stages separated by a pause.

4. The opinion of Marbut that the warped surface now represented by hilltops was essentially a peneplain with monadnocks is confirmed.

5. The date of completion of this surface appears to be post-Wilcox and preglacial. More precise dating does not appear possible at present.

6. Upwarping of this surface may be recorded by one or both of the two post-Wilcox coarse-grained units in the stratigraphic sequence underlying the Gulf embayment region.

BORDER ROCKS OF A GRANITE BATHOLITH RED LAKE, ONTARIO[1]

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ABSTRACT

Granites intrusive into basic volcanic rocks in the Red Lake area are commonly surrounded by a zone of rocks intermediate in composition between the granite and the volcanic rocks. Inclusions of varying color contrast are abundant in the granite. Study of a specific example, by means of variation diagrams and petrographic observations, leads to the conclusion that the intermediate rocks are the product of contamination of the granite magma by numerous fragments of country rocks. The contamination resulted in final-stage activity of potash-rich solutions.

INTRODUCTION

The Red Lake area, lying some hundred miles northwest of Sioux Lookout on the Canadian National Railway in northern Ontario, is one of typical pre-Cambrian geology and terrane.[2] Keewatin (?) volcanic rocks and Timiskaming (?) sediments have been intruded by granites, possibly of more than one age. The volcanic rocks are chiefly andesitic to basaltic with some dacite and rhyolite. The basic varieties have been silicified and altered to carbonate-serpentine rocks, chlorite schists, and dense hornfelsic rocks. Generally they are most altered at and near their contact with the granitic rocks. Colors vary from dark greens to grays.

The granite masses are commonly surrounded by envelopes of rocks of more basic character, and such border rocks are especially well developed on a group of islands to the southwest of Mackenzie Island at the western edge of the Mackenzie Island batholith (Fig. 1). This locality was therefore selected for a study of the processes producing the border rocks, although two circumstances render observations difficult: (*a*) the rocks outcrop on islands, and thus intermediate phases may be missing; and (*b*) the volcanic rocks of the

[1] Published with the permission of Dr. M. E. Hurst, provincial geologist of Ontario.

[2] For a complete discussion of the geology of the area refer to report by E. L. Bruce and J. E. Hawley in *Ont. Dept. Mines Ann. Rept.*, Vol. XXXVI, Part III (1927).

area have been intruded by pregranite quartz porphyry, which has considerably altered them by carbonatization and allied processes.

The contact of the granite and the volcanic rocks is most irregular, showing long tongues of dark-colored granitic material projecting into the older rocks (Fig. 1). These tongues have the composition of

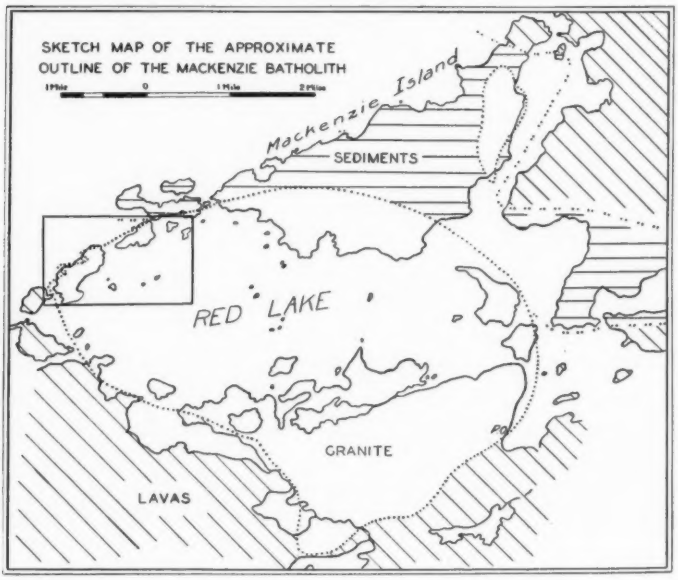

FIG. 1.—Sketch map showing the approximate outline of the Mackenzie Island batholith. The area under consideration is indicated by the rectangle.

a hornblende diorite near their contacts with the lavas but become progressively more acidic farther away, so that their material eventually grades without a break into the pinkish, coarse, alaskitic granite of the center of the batholith. The basic tongues, here termed the "border rocks" of the batholith, have sharp contacts with the volcanics. Both border rocks and volcanic rocks are cut by small dikes of granite and aplite.

Most of the exposed intrusive rock contains numerous inclusions of hornblendic or chloritic material (Fig. 2). The inclusions show all

gradations between two extremes: one extreme is easily recognizable as foreign material; the other has indefinite boundaries and is a "shadow remnant." All the inclusions are assumed to be of volcanic origin, and they range in composition from gabbro to quartz diorite; grain size varies from medium to coarse. They are noticeably most

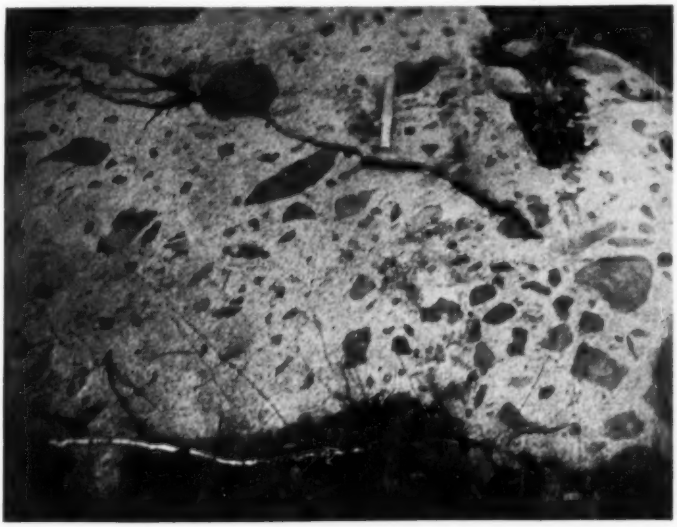

FIG. 2.—Photograph of an outcrop of granite which is rich in inclusions of hornblendic nature. The scale is suggested by the hammer. Note the variance in shape and the very faded nature of some of the fragments. This outcrop is on Mackenzie Island and is typical of the granite toward the border of the batholith.

abundant and most faded in the most basic rocks of the border. The term "faded" will be used in this paper to designate those inclusions that are shadowy and not in great contrast to the matrix.

A very complete suite of hand specimens, polished specimens, and thin sections was examined. Polished specimens were etched in hydrofluoric acid and stained in sodium cobaltinitrite to determine the approximate content of potash feldspar. Rosiwal analyses were made and results averaged and checked carefully for each type of rock. Some partial chemical analyses were carried out as an added

check. Determinations of specific gravities by means of the Joly balance correspond well with calculated specific gravities from the Rosiwal analyses.

PETROGRAPHY AND MINERALOGY

VOLCANIC ROCKS

The typical and most abundant variety of volcanic rock is a fine-grained lava composed of andesine ($Ab_{55}An_{45}$), biotite, and chlorite, with rare crystals of albite ($Ab_{90}An_{10}$). This variety will be termed the "typical volcanic." The chlorite and biotite may come from original pyroxene; however, no evidence of earlier pyroxene was noted. Some rocks, considered to be volcanic, appear under the microscope as fine-grained tangles of chlorite, epidote, and white micas, with considerable titanite in small euhedral crystals. Another type contains shreds of chlorite and white micas, highly altered plagioclase, and grains of carbonate. Some crystalloblastic quartz occurs, and porphyroblasts of biotite with a decided parallelism are scattered throughout. Magnetite and apatite are associated with the biotite. Finally, some volcanic rocks are hornfelsic, consisting of equigranular biotite, andesine, and magnetite, with minor amounts of apatite.

BORDER ROCKS

The chief minerals of the border rocks are plagioclase ($Ab_{55}An_{45}$ to $Ab_{80}An_{20}$), biotite and quartz, with minor hornblende, magnetite, and apatite. Microcline occurs to some extent, particularly in the more acidic types. Pyrite occurs in some samples. Alteration products are epidote, carbonates, and chlorite, and these minerals are more abundant in the phases of the border rocks near and against the volcanic rocks.

The plagioclase, as a rule, forms euhedral to subhedral laths with distinct zoning. Definite oscillatory zoning was not noted. Some of the rocks show a parallelism of the plagioclase laths. Microcline replaces oligoclase from the borders of crystals inward and also occurs interstitially. Microcline-perthite has partially replaced andesine, so that even the cleavages are retained. Both feldspars are apparently replaced along the borders by quartz. The quartz of the border

rocks is apparently of two ages: the earlier is interstitial; the later replaces other minerals. Small grains of quartz are found in biotite, which is embayed by quartz, and this, in turn, includes small flakes of biotite in parallel position to the larger foils. Late quartz replaces plagioclase; it embays plagioclase, leaving ragged edges.

Various intergrowths occur in which quartz replaces plagioclase. The result is usually a myrmekitic intergrowth, but in some cases there is no noticeably regular arrangement of the quartz blebs except that they are in parallel optic orientation with one another.

The biotite is dark brown and displays striking asterism of the pressure-figure type. Apatite and magnetite are associated with the biotite; commonly they occur in cracks in it or are oriented parallel to one of the rays of the pressure figure. Crystals of apatite are fresh, with well-developed crystal faces, and are most abundant in the more basic phases of the border rocks.

INCLUSIONS AND ADJACENT MATRIX ROCK

The inclusions range from quartz diorite to gabbro in composition. Under the microscope it is found that the least-faded inclusions contain andesine-labradorite and hornblende, with magnetite and apatite. The amphibole is commonly altered in great part to biotite and chlorite.

The more faded the nature of the inclusion, the more acidic its composition. Even in field exposures the inclusions of this type appear to be approaching the granitic matrix in composition. Roughly, it may be said that the borders of such inclusions are poorer in biotite and chlorite than are the centers; and frequently, as indicated by staining methods and by thin-section study, there has been a penetration of potash feldspar and quartz into the inclusion. A mineral study of such an inclusion showed that it is made up of oligoclase ($Ab_{80}An_{20}$), some andesine ($Ab_{65}An_{35}$) toward the center, biotite with or without chlorite in amount about equal to the plagioclase, and minor quartz. Magnetite is very minor. The plagioclase occurs chiefly as laths. The biotite and chlorite are frequently pseudomorphic after euhedral amphibole.

It is worthy of note that the most-faded inclusions—vague, shadowy patches in the border rocks and granite—are between the

most definite inclusions and the granite in composition. The least-faded inclusions contain hornblende, andesine, and more basic plagioclase, for the most part, whereas the matrix rocks contain minerals a step lower in the reaction series, i.e., biotite, oligoclase, and potash feldspar and quartz. The change from basic plagioclase in the centers of inclusions through oligoclase in the borders to albitic-oligoclase and potash feldspar in the matrix is parallel to the change in mineralogy and composition in the rock suite as a whole from volcanic rock to granite.

The matrix immediately adjacent to the inclusions possesses the most acidic composition of any rock type studied. Pegmatitic textures are common around many inclusions in the border rocks, particularly in the less basic phases. In thin or polished sections it can be seen that the inclusion is welded to the matrix by interpenetrating crystals of quartz and feldspar. Albite, with or without orthoclase, occurs in large crystals, many of which exhibit checkerboard structure; these crystals frequently form fairly coarse intergrowths with microcline and quartz. The albite is commonly free from twinning other than Carlsbad. The microcline is the youngest mineral. Isolated grains of quartz, in parallel optic arrangement, tend to follow some crystallographic direction, usually (010) in the feldspar. Aggregates of crystals of albite and orthoclase, each of which is only slightly disoriented optically from the neighboring crystals and in which quartz and microcline form interstitial wedges, are common around inclusions. Most of the large quartz grains are strongly fractured with the fracturing in some cases simulating a rectangular cleavage. Blocky, undulatory extinction is characteristic, and the quartz has acquired unusual biaxial properties with an optic-axial angle greater than 20°. Etching and staining of a polished specimen containing an inclusion indicates that there is a concentration of potash as orthoclase and microcline around, and penetrating into, the inclusion.

GRANITE

The granite is gradational into the border rocks. Granite from the approximate center of the batholith contains albite ($Ab_{95}An_5$) to oligoclase ($Ab_{85}An_{15}$), microcline, orthoclase and perthite, quartz, and a small amount of biotite. Magnetite, apatite, zircon, and some titanite are the accessory minerals.

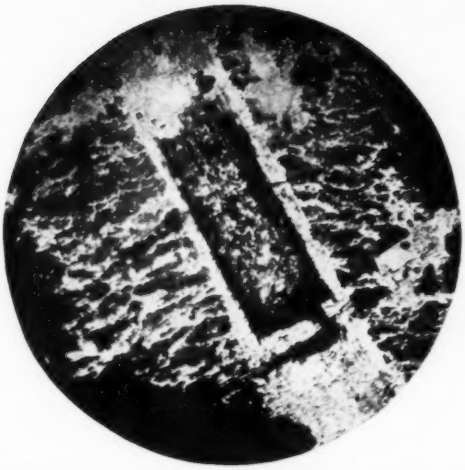

FIG. 3.—Photomicrograph of the main biotite granite, showing the formation of core-and-rim structure. The core is altered oligoclase (chlorite and white micas), surrounded by a zone of albite which has been replaced by microcline-perthite (*P*). Patches of unreplaced albite remain in the perthite. Crossed nicols, ×40.

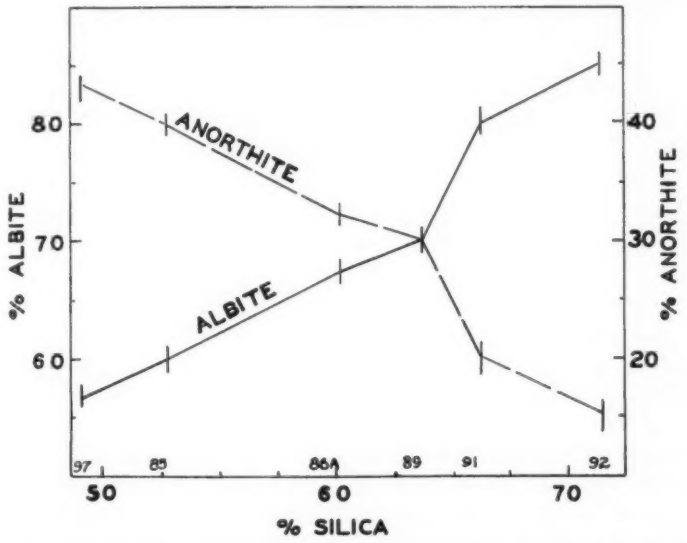

FIG. 4.—Diagram illustrating the variation in the ratio albite: anorthite in the plagioclases of the rock suite. Silica, calculated from Rosiwal analyses, is plotted as abscissa. The one deflection occurs within the granitic rocks themselves; transition into the lava is smooth. The numbers along the bottom refer to the specimens (see Table 1).

Injection and exsolution perthites, most of which are the latest rock constituents, occur interstitially around grains of plagioclase. In the biotite-rich phases of the granite there are striking fringe structures with long ribbons of perthite and microcline continuous around several crystals of plagioclase. In the granite proper, cores of oligoclase, commonly altered to white micas and chlorite, are surrounded by albite; this is replaced by microcline-perthite of the injection type. Remnants of albite are to be seen in the perthite (Fig. 3). This texture is well brought out by the etching and staining of a polished specimen.

FELDSPAR VARIATION IN THE SUITE OF ROCKS

A regular variation was found in the plagioclase from granite to volcanic rock (Fig. 4). Determinations of the feldspars by thin-section methods were supplemented by determinations of indices of refraction by oil-immersion methods. Potash content is not considered in the diagram. The only deflection in the curve occurs in the granitic border rocks themselves.

MINERALOGICAL ANALYSES

MINERAL VARIATION

There is a color gradation, dependent upon the amount of ferromagnesian minerals present, from the main granite to the typical volcanic. Rosiwal analyses of six specimens have been chosen as best representative of this change. The results (Table 1) were plotted to show the mineral variation between granite and typical volcanic (Fig. 5). The intermediate specimens represent four phases of the border rocks.

A composite of the curves for the ferromagnesian minerals drops quite regularly toward the high-silica end of the figure. A rather unusual amount of quartz occurs in one of the border rocks—a dark rock—in the hand specimen of which little quartz can be seen without differential etching. The albite molecule of the plagioclase varies within narrow limits; the anorthite molecule decreases toward the granite. Orthoclase and perthite are not separated in the diagram; perthite is in greater quantity than orthoclase even in the main granite. Orthoclase is present in the extreme border rocks only as a

constituent of three-component feldspars, but it and perthite increase rapidly toward the main granite.

The amount of apatite increases through the border rocks toward the volcanic; but few of the volcanic rocks studied contain apatite.

TABLE 1

MINERALOGICAL ANALYSES OF THE ROCK SUITE IN WEIGHT PER CENT

MINERAL	SPECIMEN NUMBERS					
	G-97	G-85	G-86A	G-89	G-91	G-92
Quartz	0.6	9.4	23.5	24.5	19.1	24.7
Orthoclase			2.4	2.6	9.5	3.0
Perthite }	3.0	2.6	.....	.....	6.7	24.3
Microcline						
Albite	36.8	37.0	34.1	42.7	42.7	36.7
Anorthite	22.6	15.6	14.4	8.5	7.9	4.3
Hornblende	0.7	.....	.....	6.5	.....	.....
Biotite	1.4	10.3	11.6	5.9	10.2	5.8
Chlorite	33.6	12.4	3.9	.....	.....	.....
Magnetite	1.2	.....	3.5	9.2	3.8	0.9
Pyrite	.....	10.7	.....	.....	.....	.....
Apatite	.....	1.1	0.5	tr.	tr.	tr.
Calcite	.....	.....	6.0	.....	.....	.....
Totals	99.9	99.1	99.9	99.9	99.9	99.7

NOTES TO TABLE 1

G-97 —"typical volcanic"; a fine-grained rock of dioritic aspect
G-85 —medium-grained dioritic border rock
G-86A—medium-grained dioritic border rock, less basic than G-85
G-89 —medium-grained biotite-hornblende-feldspar rock
G-91 —medium-grained, biotite-rich granite
G-92 —medium to coarse-grained pink granite, considered representative of the Mackenzie Island batholith

Where present it is associated with biotite and magnetite. The typical volcanic contains no measurable amount of apatite.

The irregularity of the magnetite-pyrite curve may be explained in part by the alteration of biotite to an iron-poor variety and the accompanying formation of magnetite. Such alteration could not be taken into account in the mineralogical analyses.

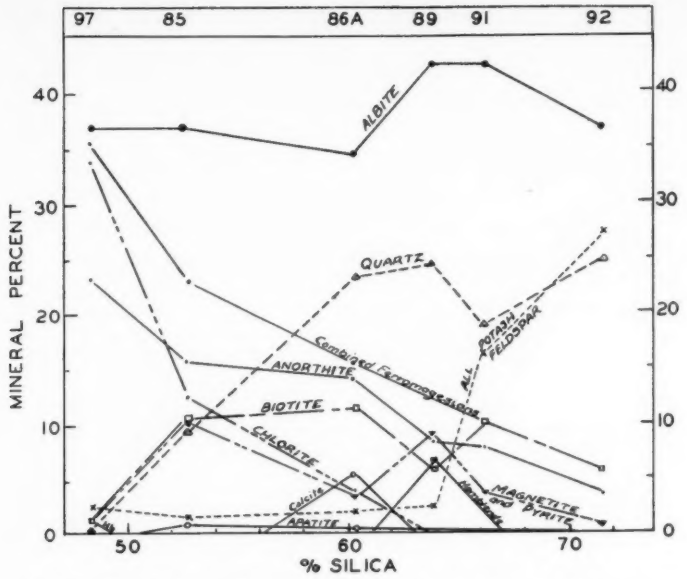

FIG. 5.—Curves of mineralogical variation in the rock suite. Weight percentage of the minerals, as determined by Rosiwal analyses, is plotted against silica, calculated from these analyses. Specimen numbers are along the top. See Table 1 for descriptions of the specimens.

TABLE 2

CALCULATED OXIDE ANALYSES FOR THE ROCK SUITE IN WEIGHT PER CENT

OXIDE	SPECIMEN NUMBER					
	G-97	G-85	G-86A	G-89	G-91	G-92
SiO_2	48.4	52.7	60.4	63.9	66.3	71.6
Al_2O_3	22.0	17.6	15.1	14.1	16.1	15.4
FeO	8.3	2.6	3.5	4.7	2.6	1.0
Fe_2O_3	1.0	0.4	3.0	7.5	3.0	1.0
CaO	4.6	4.0	6.4	1.7	1.6	0.9
MgO	6.4	4.7	2.4	1.8	1.5	0.9
Na_2O	4.4	4.9	4.0	5.0	5.3	4.3
K_2O	0.7	1.0	1.4	1.5	3.4	5.1
H_2O	3.9	1.4	0.7	0.3	0.2	0.1
P_2O_5	.....	0.5	0.2	tr.	tr.	tr.
CO_2	.....	.....	2.6	.....	.....	.....
FeS_2	.....	10.7	.....	.....	.....	.....
Totals...	99.7	100.5	99.7	100.5	100.0	100.3

OXIDE VARIATION

Mineral components of the rocks were recalculated to oxides (Table 2), and rather regular curves result in the oxide-variation diagram (Fig. 6). The rise in the CaO curve is due to the amount of carbonate in one of the specimens. Possibly this deflection should

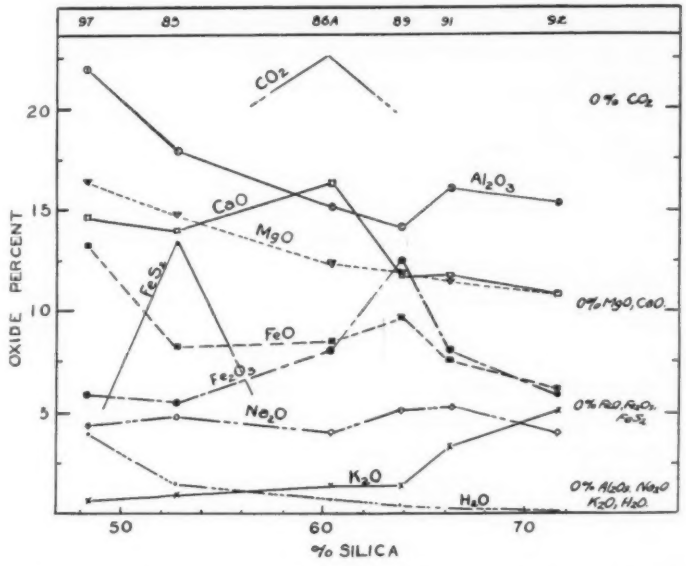

FIG. 6.—Curves of oxide variation. Weight percentage of the oxides is plotted against silica. The numbers at the top refer to the specimens.

also appear in the MgO curve, but all carbonate was calculated as $CaCO_3$. The iron-oxide curves are irregular, due in part to the calculation of biotite with an even tenor of iron and in part to irregular distribution of magnetite.

DISCUSSION OF PETROGRAPHIC FEATURES

Several features point toward unusual conditions during the emplacement of the granite. In the border rocks the plagioclase is well zoned, apatite increases from the granite to the most basic of the border rocks, pegmatitic textures occur around inclusions, and pot-

ash minerals of a late period indicate activity of potash-rich solutions.

Lack of oscillatory zoning in the plagioclase indicates that conditions changed continuously toward those in which sodic feldspar was the equilibrium phase. Continuous addition of inclusions progressively disturbed the equilibrium of the system. Certain patches —faded inclusions—in the granite and the border rocks are composed of minerals a step higher in the reaction series than the minerals of the matrix. Cooling in the liquid was too rapid to allow the cores of the plagioclases to be made over completely to sodic feldspar. However, the ill-defined nature of many inclusions does indicate that equilibrium was nearly reached in certain places; on the other hand, the presence of unusual amounts of quartz along with abundant ferromagnesian minerals and zoned, basic plagioclases indicates failure of complete equilibrium. As now seen, the rocks suggest that the process operating ceased at different stages at different points.

Hand in hand with the increase of biotite from the granite into the border rocks runs the increase of apatite. In most border rocks it is associated almost exclusively with the biotite, which has noticeable asterism. Magnetite is associated with both these minerals, and, as it commonly occurs as needles and grains parallel to one or more rays of the pressure figure, some of it at least may be later than the asterism. It is a distinct possibility that pneumatolytic processes were active during some stage of the consolidation of the border rocks; some magnetite may have been introduced at the same time. The amount of apatite present may be proportional to the amount of included basic material for the following reasons. Reactions of soda-rich solutions with plagioclase to yield more sodic feldspar may have set free certain amounts of lime, which would unite with P, Cl, or F to form apatite, if these elements were at that time being introduced from the rest magma.

The pegmatitic textures surrounding inclusions have already been described. They indicate that the inclusions had a definite chemical effect upon the granite magma. Presumably related to this pegmatitic development are the late replacements of the rock minerals by microcline, perthites, and quartz. Commonly, albite is believed to form late and to replace other minerals, that is, the end solutions

have been rich in Na_2O.[3] The replacements, fringe structures, and other microscopic evidences of the period of deposition of potash minerals are conclusive evidence that during the final stages in the rocks under discussion solutions rich in K_2O rather than Na_2O were active. This has been noted both in the main granite and in the border rocks. Possibly the normal proportion of soda to potash in the residual solutions was disturbed through reaction with basic feldspars.

If the explanation of the formation of apatite be accepted, plausibly the apatite also is late; crystals of it are fresh and cut (or are included by) all other minerals. In one example a large crystal of apatite runs continuously through magnetite, quartz, plagioclase, and white micas and biotite. If the apatite is late, then possibly the late potash-rich solutions were linked up with volatile action responsible for the apatite. Some sort of zoning may have been produced, since the apatite is more abundant in the basic border rocks, the potash minerals in the less basic phases.

ORIGIN OF THE BORDER ROCKS

Although contacts between the border rocks and the volcanic rocks are distinct lines of separation and of intrusive nature, there has been demonstrated a compositional gradation from the granite into volcanic rocks. This gradation could be explained by the differentiation of granitic magma. The greenstone inclusions in that case would have had only a physical effect on the magma, and the regularity of the variation diagrams would then be a coincidence. However, the presence of the pegmatitic zones around inclusions and the faded, indefinite nature of many inclusions are concrete evidences that the inclusions had far more than a mere physical effect on the magma.

Again, the border rocks might be true hybrids resulting from actual melting of the inclusions and later crystallization of a mixed melt made up in part of fused volcanic rocks and in part of granitic

[3] G. H. Anderson, "Granitization, Albitization, and Related Phenomena in the Northern Inyo Range of California-Nevada," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 1–74; and R. J. Colony, "The Final Consolidation Phenomena in the Crystallization of Igneous Rocks," *Jour. Geol.*, Vol. XXXI (1923), pp. 169–78.

magma. Apart from theoretical difficulties in accounting for the requisite heat supply, other objections to this theory may be found. One would, in this case, expect the matrix immediately adjacent to the inclusions to have a composition intermediate between that of the volcanic rock and the pure granite, whereas it is, in many examples, even more acidic than the granite. Also inclusions do not disappear by becoming smaller so much as by becoming more and more indefinite in outline and color contrast. The least distinct blotches have a mineral makeup almost identical with that of the granitic matrix.

If the border rocks are the result of granitization of country-rock volcanics, there should be gradational contacts between them and the volcanic rocks. But this is not the relation observed; on the contrary, intrusive relations are found.

Finally, the border rocks may be the result of reactions between the fragments of the volcanic rocks and the granitic magma. The pegmatitic zones around inclusions, the varying physical appearance of inclusions, and the demonstrated mineral (chemical) changes accompanying the fading-out of the inclusions all point to this suggestion. The scarcity of hornblende in the border rocks may be explained by reaction. If the magma had been just saturated with respect to biotite and if it received hornblendic inclusions, it could not dissolve the hornblende but would react with it to make it over to the mineral phase—namely, biotite—in equilibrium with the magma. By this reaction the magma would precipitate more than the normal amount of biotite, while being enriched in some substances originally in the hornblende but not needed to form biotite. Similarly, the magma would react with basic plagioclases of the inclusions to produce more sodic varieties. This reaction hastens the routine of crystallization of the liquid; the final stage is the production of pegmatitic rest magma in small but noticeable amounts.

Many petrologists have studied problems similar to the one under consideration. G. W. Tyrrell[4], M. MacGregor,[5] and S. R. Nockolds[6]

[4] *The Principles of Petrology* (New York: Dutton & Co., 1929), pp. 163 ff.

[5] "The Evolution of the Criffel-Dalbeattie Quartz Diorite: A Study of Granitization," *Geol. Mag.*, Vol. LXXII (1935), pp. 481–96.

[6] "The Petrology of Barnavave," *Geol. Mag.*, Vol. LXXII (1935), pp. 289–315.

speak of "reciprocal reaction" whereby the magma becomes more basic and basic xenoliths more acidic. The conclusions reached above are in agreement with N. L. Bowen.[7]

Staining indicates that potash minerals foreign to the invaded rocks occur around inclusions. The feldspar of the inclusions averages oligoclase, and if the inclusions were originally of basic volcanic rocks, much soda must have been added.[8] H. L. Alling states that, if an inclusion is rich in lime, soda transfuses more rapidly than potash; but, if the inclusion is rich in magnesia, potash transfuses more readily than soda.[9] Now if soda has been added through metasomatism to the plagioclases of the inclusions, lime must have been removed. Thereafter, magnesia may have been in greater proportion to lime, and therefore potash was added. This order agrees with the finding of late potash minerals in the border rocks. Since the borders of inclusions are frequently poorer in biotite and in chlorite than are the centers, perhaps this indicates a migration of lime and magnesia into the granite magma to balance the addition of soda and potash to the inclusion. In other words, the process is reciprocal reaction, an attempt at establishment of equilibrium between the basic inclusions and the granite magma.

CONCLUSIONS

The first step in the formation of the heterogeneous border rocks was the mechanical inclusion of fragments of basic volcanic rocks in the granite magma. Reactions proceeded between the magma and the inclusions with simultaneous precipitation of minerals in the magma to provide the heat necessary for the reactions. In places a final pegmatitic liquid was formed, and this crystallized chiefly around the inclusions, where it formed.

However, there was replacement of the constituents of the resulting hybrid rocks by minerals deposited from solutions containing K, Na, Fe, and Si, perhaps associated with such volatiles as P, Cl, F, O,

[7] *The Evolution of the Igneous Rocks* (Princeton: Princeton University Press, 1928); and R. C. Emmons, "Concerning Inclusions in Igneous Magmas," *Jour. Geol.*, Vol. XXXIV (1926), pp. 422–28.

[8] To the writer's knowledge there are no spilitic volcanic rocks in this area.

[9] *Interpretative Petrology* (New York: McGraw-Hill Book Co., 1936), p. 256.

and OH, since minerals such as microcline, quartz, magnetite, and biotite and possibly apatite are late, secondary, or replacement minerals. The predominance of potash in the final-stage solutions is to be stressed as it may have some bearing on the formation of sericite in many ore deposits. This was a continuous process, interruption of which at various stages produced rocks of considerable mineralogical variety.

The diagrams showing the variation of the plagioclases and of mineral and oxide compositions adequately bear out the postulate of contamination of the granite magma by reaction with foreign material.

ACKNOWLEDGMENTS.—The rock specimens and data for research were gathered during the summers of 1937 and 1938 while working under the direction of Dr. H. C. Horwood of the Ontario Department of Mines. To Dr. Horwood the writer is indebted for many suggestions. The writer wishes to thank Dr. E. L. Bruce and Dr. J. E. Hawley of Queen's University for much constructive discussion during the preparation of the original manuscript and Dr. Bruce for painstaking reading and editing of the paper. The writer also expresses his appreciation to Dr. N. L. Bowen of the University of Chicago for giving of his time in further reading of the manuscript.

A PRE-CAMBRIAN GNEISS FROM THE SAN RAFAEL SWELL, UTAH

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ABSTRACT

A drilling unit of the California Company penetrated pre-Cambrian gneiss in the San Rafael swell, Utah. A detailed microscopic description of the rock and its minerals is presented. The mineralogical composition and many of the textural features indicate that the gneiss had an igneous origin and should be named a "granodiorite gneiss." The foliation was probably caused by flow of the partly crystallized magma. The early separation of the plagioclase in the form of large tabular grains is an important factor contributing to the foliation and inequigranularity of the rock and accounts for the high degree of orientation of the plagioclase grains parallel to the plane of foliation. The survival of many typically igneous features is strong evidence that the gneiss was not foliated or recrystallized after its complete solidification.

INTRODUCTION

A foliated pre-Cambrian rock in the San Rafael swell of the Colorado Plateau was penetrated by a well drilled in 1939 by the California Company. The well is at the center of the NW. $\frac{1}{4}$ of the NW. $\frac{1}{4}$ of Sec. 27, T. 23 S., R. 11 E., Emery County, Utah. This location is about 85 miles from the nearest pre-Cambrian exposures eastward and northwestward and about 150 miles from those southward, and it is believed, therefore, that the rock should be described thoroughly as a matter of record.

The study has been made on a 4-inch core sample taken 4,400 feet below the surface and from about 40 feet below the base of the sedimentary rock series. The entire sequence of sedimentary rocks is believed to be Paleozoic,[1] although it is possible that 110 feet of red arkosic grit at the bottom belong to the Proterozoic.

MEGASCOPIC FEATURES

The rock is medium gray and somewhat mottled with pink patches. The gray color is due to the presence of a large amount of plagioclase mixed with a small amount of biotite. The pink patches are granular aggregates of potash feldspar which are usually less than

[1] Personal communication, A. J. Eardley.

1 cm. in diameter and are irregular in shape and in distribution. Many of the plagioclase grains are 2–4 mm. long and have a tabular habit. The large plagioclase grains are embedded in a groundmass that has an average grain size of about $\frac{1}{2}$ mm.

The rock is strongly foliated. The thickness of the laminae ranges from 1 to 3 mm., giving a schistose appearance. The gneiss is very tough but breaks most easily parallel to the plane of foliation. There is also a noticeable tendency for it to break in a plane perpendicular to the foliation. The plane of foliation makes an angle of 50°–60° with the axis of the core.

MICROSCOPIC FEATURES

MINERALOGICAL COMPOSITION

Plagioclase, potash feldspar, quartz, and biotite constitute about 95 per cent of the gneiss. The accessory minerals include magnetite, pyrite, rutile, garnet, apatite, and zircon. The rock has undergone a moderate amount of alteration most of which is confined to the plagioclase with sericite as the alteration product. Small amounts of calcite and partly chloritized biotite are localized near the potash-feldspar patches. The essential optical properties of the more important minerals are presented in Table 1.

The quantitative mineralogical composition of the gneiss is summarized in Table 2. A five-spindle Wentworth recording micrometer was used to obtain the data. The traverses were made at right angles to the plane of foliation on thin sections cut perpendicular to the foliation. The modal analyses of three sections, in volume percentage, are listed in columns 1, 2, and 3. The weighted average for the three sections is given in column 4 and is based on the average length of traverse. Column 5 records the weight-percentage analysis derived from column 4 by multiplying each item by the corresponding density as given in column 6 and recalculating to 100 per cent. It is evident from the modal analyses that the gneiss is somewhat inhomogeneous. Potash feldspar especially has an irregular distribution.

TEXTURE AND STRUCTURE

The granitic texture of the gneiss is highly modified by marked inequigranularity of the minerals, foliation, and preferred orientation

TABLE 1

THE COMPOSITION AND OPTICAL PROPERTIES OF THE IMPORTANT MINERALS

Mineral	Composition	Refractive Indices	Other Optical Properties	Remarks
Plagioclase	$An_{62}-An_{36}$ Aver. $= An_{48}$	On (001) $n_1 = 1.559$ $n_2 = 1.553$	On (001) Extinc. $< = 6°$	Twinning: albite common, pericline rare Zoning: normal type, continuous
Orthoclase	$Or_{90}Ab_{10}-$ $Or_{60}Ab_{40}$, Aver. $=$ $Or_{80}Ab_{20}$	$\alpha = 1.519$ $\beta = 1.524$ $\gamma = 1.526$	$2V = 50°-60°$, On (001) Extinc. $< = 0°$, On (010) Extinc. $< =$ $4°-10°$,	Film and string perthite abundant String perthite noticeable in grain borders. Carlsbad twinning infrequent
Microcline	$Mi_{80}Ab_{20}-$ $Mi_{70}Ab_{30}$	Similar to orthoclase		Less perthitic than orthoclase Carlsbad twinning infrequent Quadrille twinning prominent
Quartz			Wavy extinction	Fluid inclusions abundant in many grains, absent in others
Biotite	FeO = 26%* MgO = 7%	$\alpha = 1.603$ $\gamma = 1.663$	$2V = 0°-5°$	Pleochroism: light yellow-brown to dark orange-brown
Garnet	$Al_{68}Py_{21}$ Sp_6Gr_5 wt. %	$n = 1.792$		MnO = 2.5% by colorimetric analysis Pale pink color in thin section Density = 4.10 ± 0.05

* F. F. Grout, "Notes on Biotite," *Amer. Min.*, Vol. IX (1924), p. 163.

TABLE 2

MODAL ANALYSES OF THE GNEISS

Mineral	Volume Per Cent			Weighted Average	Weight Per Cent	Density
	1	2	3	4	5	6
No. of traverses	11	22	24	.....	.....	.....
Total traverse in millimeters	157.77	379.01	441.74	.....	.....	.....
Plagioclase	39.1	35.8	35.5	36.6	35.1	2.69
Potash feldspar	9.1	10.6	16.7	12.4	11.3	2.57
Quartz	32.1	30.1	30.0	30.6	29.0	2.66
Biotite	17.0	17.1	13.3	15.7	17.5	3.12
Garnet, magnetite, etc.	2.7	6.4	4.5	4.0	5.8	4.10
				0.7	1.3	5.13
Total	100.0	100.0	100.0	100.0	100.0	.....

TABLE 3

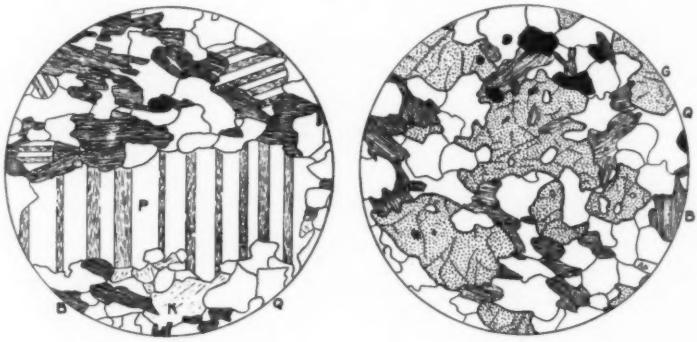
TEXTURAL AND STRUCTURAL RELATIONSHIPS OF THE MINERALS

Mineral	Grain Size (mm.)	Grain Habit	Relationship to Other Minerals
Plagioclase	0.1—3.0 Aver. = 1+	Anhedral; large grains tabular parallel to (010), small ones equidimensional	The larger grains are imbedded in a finer-grained groundmass. Tabular grains tend to be oriented parallel to plane of foliation
Biotite	0.1—0.4	Subhedral, tabular parallel to (001). Grains tend to cluster in subparallel orientation	A few grains are included in the garnet and in the outer portions of the large plagioclase grains. Mostly intergrown with quartz. Tabular grains tend to be oriented parallel to plane of foliation
Quartz	0.01—1.0 Aver. = 0.2	Anhedral, equi- and inequidimensional	A few grains are included in outer portions of the large plagioclase grains. Mostly intergrown with biotite and garnet. A few grains are elongated parallel to the plane of foliation and have rows of fluid inclusions transverse to length
Potash feldspar	0.01—1.0 Aver. = 0.2	Anhedral; large grains tend to be equidimensional	The smaller grains appear to be interstitial. The larger grains occur only in the feldspar-quartz aggregates that comprise the pink patches of the gneiss. The texture is distinctly granitoid in these aggregates
Garnet	0.5—2.0	Anhedral; very irregular	Occurs intergrown with quartz and contains biotite inclusions. No inclusions of potash feldspar were observed. Many grains are elongated parallel to the plane of foliation
Magnetite	Small	Euhedral and anhedral	Small octahedrons occur in some of the calcic cores of the plagioclase grains
Pyrite	Small	Anhedral	A very small amount occurs as inclusions in magnetite and biotite
Rutile	Small	Anhedral	A very small amount occurs as small grains associated with magnetite
Apatite	Small	Mostly euhedral, prismatic	Uniformly distributed in rock.
Zircon	Small	Mostly anhedral	Uniformly distributed in rock. Causes pleochroic halos in biotite

of the plagioclase and biotite grains. The essential textural and structural relationships of the minerals are recorded in Table 3 and partially illustrated in the camera lucida drawings of Figure 1, *A* and *B*.

PETROFABRIC ANALYSIS

As an aid in interpreting the history of the gneiss, a petrofabric analysis was made on biotite and quartz (Fig. 2, *A* and *B*). The



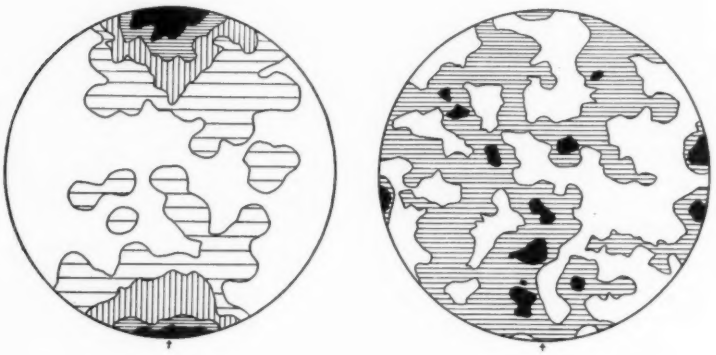
A *B*

FIG. 1.—*A:* The large-zoned plagioclase grain (*P*) is cut nearly perpendicular to an optic axis and shows faint traces of pericline twinning (shaded bands). The small grains of plagioclase show albite twinning. The groundmass consists of quartz (*Q*), biotite (*B*), orthoclase (*K*), and magnetite (black). Diameter of field is about 1.77 mm. *B:* Irregular grains of garnet (*G*) enclose and are intergrown with quartz (*Q*), biotite (*B*), and magnetite (black). Diameter of field is about 1.77 mm.

perpendiculars to (001) of 200 biotite grains were measured. The diagram clearly reveals the marked tendency of the elongated biotite plates to be parallel to the plane of foliation (S_1). The long diameters of the plates are parallel to the intersection of S_1 and a plane of cleavage lying in the plane of the diagram (S_2). No significant secondary maximum parallel to S_2 appears in the diagram.

Although no petrofabric diagram of plagioclase was made, a study of the hand specimen and the thin sections indicate the following relationships. Many of the plagioclase grains are tabular parallel to (010). These tabular grains have a noticeable tendency to be oriented with (010) parallel to S_1 and (001) parallel to S_2. If the per-

pendiculars to tabular sections of plagioclase were plotted, a diagram much like that obtained for biotite would result, although the orientation would be less perfect. The smaller and more equidimensional grains have a more random orientation. The (001) cleavage of the oriented plagioclase is believed to be responsible for the tendency of the gneiss to split parallel to S_2. The (010) cleavage of plagioclase and the (001) cleavage of biotite explain the ease of separation parallel to S_1.



A *B*

FIG. 2.—*A:* Diagram of 200 biotite grains, perpendicular to (001). Nonselective. Contour interval in per cent: 10–8–5–2–0.5–0. *B:* Diagram of 400 quartz axes. Nonselective. Contour interval in per cent: 2.5–2–1–0.

Measurements of the quartz axes were made on the same thin section used for biotite. The diagram shows nearly random distribution. Although 400 grains were measured, the highest concentrations are only 2 to 2.5 per cent. The significance of the diagram is uncertain. There may be a tendency for a girdle to form around the *B*-axis. Selective elemental diagrams and tests for homogeneity of fabric are needed to prove the point. It is generally true, however, that recrystallized quartz due to dynamic metamorphism tends to show concentrations of about 5 per cent, which is higher than here obtained.

The petrofabric data may be explained on the assumption that we are dealing with a fusion tectonite, that is, a primary gneiss. In

unimpeded laminar flow the tabular but elongated plagioclase and biotite grains would tend to become oriented with the tabular faces in the plane of flow and the long axes parallel to the *B*-axis of rotation.[2] The quartz would only be expected to show a weak orientation, possibly as a girdle about the *B*-axis.

CHEMICAL COMPOSITION

It has not been possible to have a chemical analysis made of the gneiss. As a substitute, the chemical composition has been calculated using the average modal analysis and the density figures listed in Table 2 (see Table 4). Some indication of the accuracy of the modal

TABLE 4

CALCULATED CHEMICAL COMPOSITION OF THE GNEISS

	Per Cent		Per Cent
SiO_2	65.2	CaO	3.7
TiO_2	0.4	Na_2O	2.3
Al_2O_3	15.6	K_2O	3.1
Fe_2O_3	2.3	H_2O+	0.7
FeO	5.2		100.0
MnO	0.2		
MgO	1.3		

analysis is shown by a comparison of the true specific gravity of the rock with that calculated from the mode. The specific gravity of the powdered rock, determined by the picnometer method, is 2.811. The calculated specific gravity is 2.807.

The composition of the plagioclase used in the computations is $Ab_{46}Or_6An_{48}$ mol per cent. According to H. L. Alling[3] the Ab molecule of andesine-labradorite is replaced by about 6 mol per cent of the potash-feldspar molecule on the average. The compositions for potash feldspar and biotite are taken from works by O. Andersen[4] and A. Johannsen.[5] The garnet is calculated according to the formu-

[2] E. B. Knopf and E. Ingerson, "Structural Petrology," *Geol. Soc. Amer., Memoir 6* (1938), pp. 137–39.

[3] "The Mineralogy of the Feldspars, Part I," *Jour. Geol.*, Vol. XXIX (1921), pp. 194–283.

[4] "The Genesis of Some Types of Feldspar from Granite Pegmatites," *Norsk geol. tidssk.*, Vol. X (1928), p. 146, No. 9.

[5] *Petrography of the Igneous Rocks*, Vol. II (1932), p. 343, No. 74*a*.

la given in Table 1, and magnetite according to its theoretical composition. The alteration products are not included in the calculations, but this omission introduces only a slight error.

The calculated chemical composition falls within the range given for granodiorites. The most unusual feature of the composition is the high iron oxide content. It is possible that the water content is 1–2 per cent too low.

GEOLOGIC HISTORY OF THE GNEISS

CRITERIA FOR AN IGNEOUS ORIGIN

Below are listed the various criteria that suggest an igneous and not a sedimentary origin for the gneiss. Few of the items mentioned constitute conclusive evidence in themselves for such an origin, but they make a convincing array when viewed collectively.

1. Qualitatively and quantitatively the mineralogical composition corresponds to a granodiorite.

2. Small octahedrons of magnetite occur rather abundantly in the calcic plagioclase.

3. Small grains of zircon and apatite are uniformly distributed throughout the rock. Many of them are euhedral.

4. What appears to be primary pyrite occurs in biotite and magnetite.

5. Fluid inclusions occur abundantly in the quartz.

6. Myrmekitic intergrowths and corroded plagioclase grains are suggestive of a late stage of crystallization.

7. Thin, oriented perthitic stringers of albite occur in the potash feldspar which are probably the result of exsolution.

8. A few of the larger grains of orthoclase and microcline show Carlsbad twinning.

9. The size and shape of many of the plagioclase grains suggest crystallization from a magma.

10. Most of the large plagioclase grains show a continuous type of zoning with cores of calcic labradorite and borders of sodic andesine.

11. The order of crystallization for the most part appears to be typical of a granodiorite.

METAMORPHISM

If the gneiss has had an igneous origin, as the criteria above strongly suggest, two explanations for the origin of the foliation appear possible. The foliation may be a primary structure of the igneous rock caused by flow of the magma during crystallization, or it may be a secondary structure induced in completely solidified rock by recrystallization due to differential pressure. Each kind of foliation has its characteristic criteria.

It is very doubtful if features indicating an igneous origin such as continuous zoning of the plagioclase, the tabular development of a part of the plagioclase, the finely perthitic nature of the potash feldspar, the Carlsbad twinning of the potash feldspar, the distinctly interstitial character of the potash feldspar, and the apparently normal order of crystallization of the minerals, can either originate or be preserved under any conditions of metamorphism that cause recrystallization of the rock. The foliation of the gneiss depends on the tabular habit and the orientation of the larger plagioclase grains. It is doubtful if partial recrystallization can account for such foliation. One concludes that the foliation, mineral orientation, and other features of the rock that might be interpreted as metamorphic are really primary structures and may be satisfactorily explained by postulating a flowing of the granodioritic magma during crystallization and the application of strong directional pressure in the late stages of crystallization.

THE CRYSTALLIZATION HISTORY

Scattered grains of some of the accessory minerals were the earliest to crystallize from the granodioritic magma, and they were soon followed by sodic bytownite or calcic labradorite. The most calcic cores of plagioclase show little or no zoning which suggests that the rate of cooling in the early stage of crystallization was slow. A faintly perceptible break between the core and the continuously zoned portions of a few of the large plagioclase grains suggests that either the rate of cooling of the magma suddenly increased, probably due to injection of the magma into cooler portions of the crust, or, that some of the plagioclase grains were partially resorbed, possibly due to sinking into warmer regions of the magma chamber.

The amount of plagioclase that crystallized before biotite and quartz appeared cannot be estimated with any certainty, nor can it be determined which of the two minerals—biotite or quartz—was first to crystallize. Biotite was probably the second essential mineral to appear, but quartz must have started to crystallize not long afterward, because small inclusions of it are found rather deeply enclosed in some of the large plagioclase grains, although not in the most calcic cores.

As soon as the plagioclase and biotite grains assumed tabular forms they tended to adjust themselves to the most stable position in the flowing magma. Petrofabric studies indicate that the most stable position of tabular particles in a laminar-flowing medium is attained when the tabular faces are parallel to the plane of flow. The ability of the magma to flow freely decreased with advancing crystallization, and, finally, the condition was reached when the grains were often jammed together during movement. A magma that has crystallized to the extent of 60–75 per cent probably would have enough rigidity to transmit shearing stresses. Many of the larger plagioclase grains are thought to have been fractured in this way.

If any of the quartz grains were crushed, later additions on the particles, in optical continuity, have concealed this fact. A few of the quartz grains are greatly elongated parallel to the plane of foliation. They are considerably strained and have rows of fluid inclusions transverse to the length of the grains. Such quartz grains are in close proximity to equidimensional grains that show less strain and have unoriented fluid inclusions. It is thought that the elongation was acquired either by crystallization under a condition of differential pressure or by local recrystallization under such a condition. It is reasonably certain that most of the quartz has not recrystallized either before or after the complete solidification of the magma.

It is possible that some of the biotite grains had recrystallized before complete solidification of the magma. In such a case it is easy to imagine that the biotite would show metamorphic characteristics similar to those that are observed in many metamorphic rocks.

Inclusions of all minerals except potash feldspar are found in the

garnet, which suggests that the garnet had completely crystallized before the potash feldspar started to crystallize. Quartz was the principal contemporary crystallization product with the garnet. The garnet was later than part of the biotite, possibly later than all of it. Little is known of the physical-chemical conditions that cause the formation of garnet. Differential pressure may possibly affect equilibrium conditions in such a way as to favor the formation of this mineral. It is interesting to note that most of the garnet grains in the gneiss are somewhat elongated parallel to the plane of foliation.

By the time the potash feldspar began to crystallize about 70–80 per cent of the magma had solidified. The residual magma was greatly enriched in water vapor which caused it to remain in a very fluid condition in spite of the relatively low temperature. This is indicated by the large size of some of the potash feldspar and associated quartz grains.

Many writers have called attention to solid solution between the potash feldspar molecule and the soda feldspar. According to the phase diagram the first crystals to separate from a melt of the composition $Or_{80}Ab_{20}$ will be richer in the potash molecule than the liquid. If cooling is so rapid that equilibrium cannot be maintained between solid and liquid, the result will be zoned crystals whose borders will be richer in the soda molecule than the core. Below a certain temperature exsolution will begin along the borders of the grains and progress toward the center. The perthitic intergrowth may not reach the center, because orthoclase apparently is capable of retaining a small amount of albite in solid solution at low temperatures.

It is interesting to note that many of the orthoclase grains show such a relationship. The extinction angle on (010) increases directly with the amount of albite stringers. If the perthite were formed by replacement, the above relationship would not be likely to hold.

The microcline was probably the last mineral to crystallize from the magma. According to E. Spencer[6] the optimum condition for

[6] "The Potash-Soda-Feldspar, II: Petrogenesis," *Min. Mag.*, Vol. XXV (1938), pp. 87–116.

the formation of microcline occurs when crystallization falls within the exsolution temperature range of 450°–750° C. He has shown that microcline can invert to sanidine and that the inversion is probably reversible. In view of this recent work it is reasonable to conclude that the orthoclase crystallized when the temperature was above the inversion point, or inversion range, and microcline became the stable form at a lower temperature.

Corrosion of the plagioclase by the potash feldspar occurs only in the large potash-feldspar aggregates. Calcite and partly chloritized biotite are also closely associated with these aggregates. These features suggest that the potash-feldspar aggregates mark the location of channels through which the rest-magma and deuteric solutions circulated.

Apparently differential pressure affected the granodiorite through the last stages of crystallization. A few of the potash-feldspar grains are strained and have a disjointed appearance. The fractured garnet and strained quartz grains are likewise indicative of stress during the late stage of crystallization.

It is impossible to estimate the extent of the granodiorite body, but it is likely that it completely underlies the San Rafael swell. The nearest pre-Cambrian outcrops with which the writer is familiar are in the Wasatch Mountains, 75–100 miles NNW. of the San Rafael swell.[7] No rock similar to the gneiss has been found there.

ACKNOWLEDGMENTS.—The writer is indebted to J. M. Kirby, district geologist of the California Company, for the core specimen and for securing permission to publish a description of it. The study was made at the suggestion of A. J. Eardley. The writer acknowledges the helpful criticisms of W. F. Hunt, T. S. Lovering, and A. J. Eardley, of the University of Michigan.

[7] A. J. Eardley and R. A. Hatch, "Pre-Cambrian Crystalline Rocks of North-Central Utah," *Jour. Geol.*, Vol. XLVIII (1940), pp. 58–72.

REVIEWS

Geology of Coal. By OTTO STUTZER. (Translated and revised by ADOLPH C. NOÉ.) Chicago: University of Chicago Press, 1940. Pp. 461; figs. 197. $5.00.

The publication of this excellent translation of the late Dr. Otto Stutzer's *Kohle* constitutes a welcome addition to our literature on coal and its geology. Most coal chemists, technologists, and geologists have had occasion to use the original German text as a reference book and will appreciate this more easily available presentation of Dr. Stutzer's comprehensive work. This is especially true because the translation by the late Dr. Noé presents the original text accurately and in smooth, easily readable English.

The volume consists of nine chapters, entitled: (i) "Definition of Coal," two pages; (ii) "Coal as a Rock," forty-eight pages; (iii) "Microscopic Examination of Coal," thirty-seven pages; (iv) "The Origin of Coal," thirty-nine pages; (v) "The Processing of Coal," five pages; (vi) "Origin of Coal Beds," fifty-two pages; (vii) "Stratigraphy of Coal Deposits," sixty-six pages; (viii) "The Petrography of Coal Beds," eighty-three pages; and (ix) "Disturbances of Coal Beds," one hundred and four pages. There are one hundred and ninety-seven illustrations, most of which are excellent line drawings and photomicrographs. A total of almost nine hundred references are given in groups at the end of each chapter. The citations are clear and constitute an excellent bibliography of coal literature. References are made in the text by giving the name of the responsible author and the date, which permits correlation with the list of references. Finally, tables of weights, measures, and energy units, a good general index, an index of authors, and an index of places are appended. The typography is excellent.

Perhaps the greatest value of *Geology of Coal* is that it presents the European point of view on coal studies by an eminently qualified student. Furthermore, each point is thoroughly illustrated by well-chosen examples mostly from European occurrences and European literature. In accordance with European custom the composition of coal is presented consistently by use of the ultimate analysis. The addition of proximate analyses at a number of points in the text would have constituted additional helpful translation into American scientific thought.

Many phases of the geology of coal are discussed authoritatively and

in relatively complete detail. Of these, the discussions of coal balls and related materials and of gases in coal are most impressive to the reviewer. The discusson of coal balls naturally reflects the thorough knowledge of Dr. Noé in that field. However, the broad scope of this dissertation and the necessary space limitations result in a somewhat didactic treatment of some points, a feature of regret to research workers who, naturally, desire exhaustive detailed treatment. It is the reviewer's opinion that this shortcoming is more than counterbalanced by the increased value of the work as a textbook and general reference book for instructors of economic geology, mining engineers, and geologists engaged in coal studies.

Dr. Stutzer's *Kohle* has long commanded the respect of students of coal, and they should be grateful to the late Dr. Noé for his excellent translation.

THOMAS A. HENDRICKS

Scenery of Florida Interpreted by a Geologist. By C. WYTHE COOKE. (State of Florida, Department of Conservation, Geological Bull. 17.) Tallahassee, Fla., 1939. Pp. 118; figs. 58.

Dr. Cooke of the United States Geological Survey has written this report for the layman as well as for the trained geologist wishing a reconnaissance survey of the stratigraphy and physiography of Florida. The simplification of the geological vocabulary makes it a good reference book for tourists with a desire to understand what lies back of the scenery. However, the detailed geomorphological descriptions are not lost by this means of presentation. The reader is struck by the dominant part that fluctuations of sea-level on the Floridian plateau have played in the forming of the present land surface.

The book is amply illustrated with good photographs and diagrams and has a complete index and bibliography.

LOUISE BARTON FREEMAN

Geological Investigations in East Greenland, Part III: *The Petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland.* By L. R. WAGER and W. A. DEER. ("Meddelelser om Grønland," udgivne af Kommissionen for Videnskabelige Undersølgelser I Grønland, Vol. CV, No. 4.) Kobenhavn: C. A. Reitzel, 1939. Pp. 352; figs, 68; pls. 27; maps 1. Kr. 20.

A remarkable iron-olivine gabbro was discovered in 1930 during a brief stay of the British Arctic Air-Route Expedition in Kangerdlugssuaq. This

report is the result of several expeditions made by the authors since that time.

The rocks of the Skaergaard intrusion are divided into two natural groups—layered series and a border group. The origin of the layered group, which resembles bedded red sandstone from a distance, is explained by convection currents resulting in a separation by specific gravity of the light from the heavy components, and by igneous lamination due to the tendency for the plagioclase to assume a platy habit. The authors draw an analogy between the structural features of the layered series and sedimentary rocks, the igneous laminations being similar to the lamination of a micaceous silt, in both cases due to the lamellar form of the material deposited and to the rhythmic layering, similar to graded bedding except that specific gravity is substituted for size grading. The border group, which is much less in bulk than the layered series, occurs everywhere between the central layered series and the steep transgressive margin of the intrusion. It is material solidified along the top and sides of the magma chamber, where there was rapid loss of heat.

Detailed analyses of many samples of the intrusion are given with numerous very good photomicrographs of thin sections.

LOUISE BARTON FREEMAN

The Upper Triassic Flora of Arizona. By L. H. DAUGHERTY and H. R. STAGNER. (Pub. 526.) Washington: Carnegie Institution of Washington, 1941. Pp. 108; pls. 34; figs. 1. Paper cover, $1.25; cloth bound, $1.75.

A modern treatment of the fossil flora from the upper Triassic of Arizona has been needed for some time. The basis of this study is material collected from a number of new localities in the Petrified Forest National Monument.

This flora assemblage from Arizona and New Mexico is represented by thirty-five genera belonging to six classes and eleven orders. Most fossil-bearing horizons occur in the Shinarump and lower Chinle. Their scarcity in the upper Chinle is apparently due to increased aridity at that time. It is concluded that the lower Chinle plants lived in tropical to subtropical temperatures with sufficient precipitation to insure permanent streams and swampy conditions in the lowlands. Rains fell at periodic intervals separated by intensely dry spells. The writers compare the climate with that of the tropical savannas today. Evidence is presented

to show that the plants, in part at least, grew *in situ* and did not undergo the extensive transportation which some students have indicated.

The most closely related flora is that of the Newark Basin, which has, in common with the Chinle, six identical and six closely related species. The differences noted are in part due to climatic conditions. Other floras with which the Chinle is compared are those of the Dockum of Texas, the Poleo sandstone of New Mexico, the Rhaetic of Greenland, the Sonora Triassic of Mexico, the Keuper of Germany, and the Rhaetic of Japan. Correlation of the Chinle, on paleobotanical evidence, is with the the Newark Triassic and the Keuper of Germany.

The latter part of the publication is devoted to a systematic and, in so far as possible, morphologic description of each form. Many new genera and species are erected. Under each species is a short systematic diagnosis, a more complete morphological description, and a discussion. In some cases the morphological studies are very complete; for example, *Lyssoxylon grigsbyi* has seven pages devoted to the following structures: the base of the petiole, the stem, secondary xylem, primary xylem, medulla, and a possible peduncular scar. Each description is accompanied by excellent photomicrographs which, where possible, depict not only cross sections, but tangential and radial sections as well.

An excellent bibliography and systematic index are included.

ERNEST P. DU BOIS

The American Empire. Edited by WILLIAM H. HAAS. Chicago: University of Chicago Press, 1940. Pp. xi+408. $4.00.

Not geological in scope, this volume makes excellent reading for anyone who is interested in United States possessions, their geographical settings, history, economic problems, and their peoples. An introductory chapter on the motives for acquiring each major possession is followed by chapters on Puerto Rico, the Virgin Islands, Panama Canal Zone, Alaska, Hawaii, and the Philippines. A final chapter discusses "Manifest Destiny" and concludes that the good we have done in these possessions far outweighs any harm which we have inflicted.

The illustrations are good, although small. Written by a number of authors, the style is remarkably uniform, indicating careful editing.

C. W. STERNBERG